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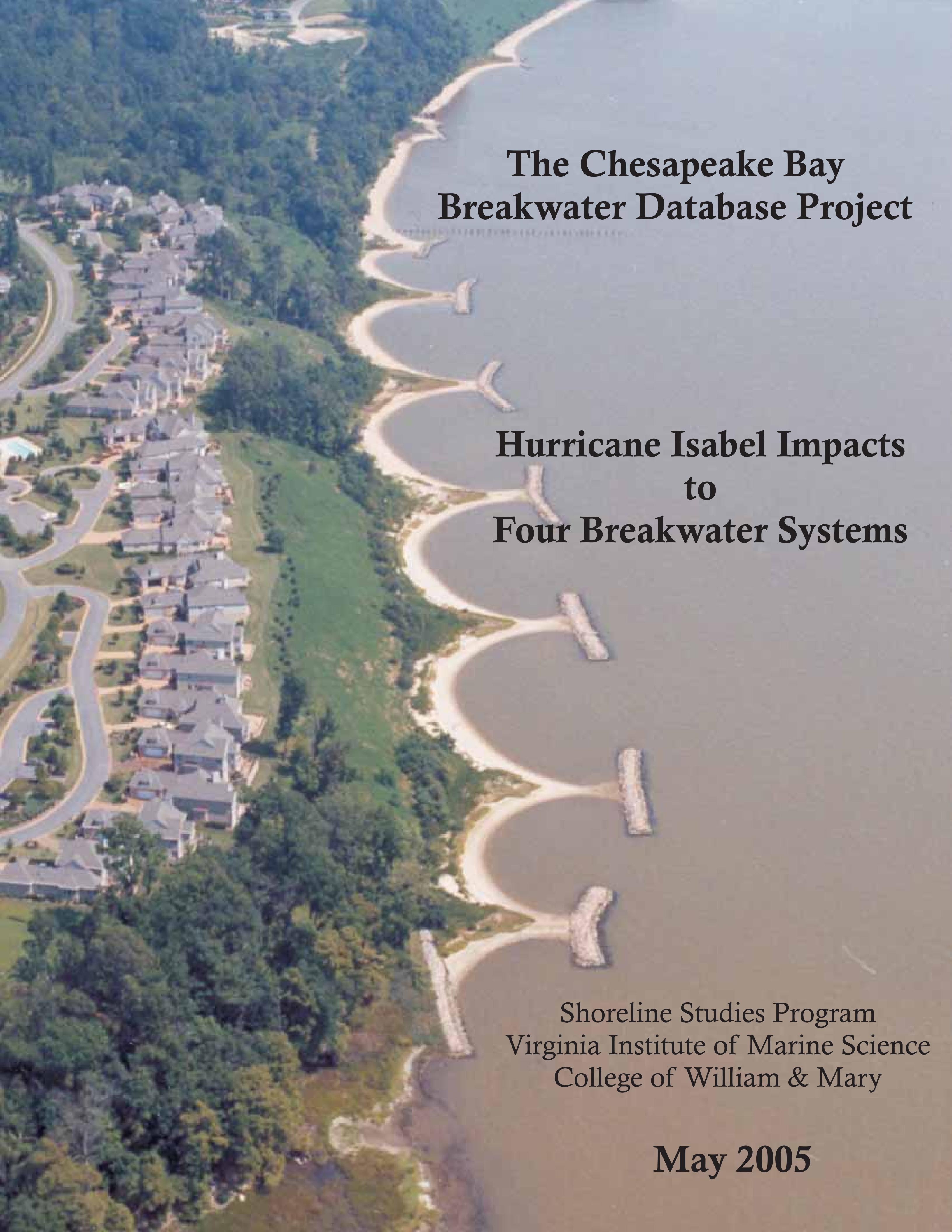

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Shoreline Studies Program
Virginia Institute of Marine Science
College of William & Mary

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Cover Photo: Kingsmill 26 August 2004 by Shoreline Studies Program

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1 Introduction

Hurricane Isabel impacted Chesapeake Bay on September 18, 2003 with record high storm surge and winds. Virtually all Chesapeake Bay shorelines were impacted. Those shorelines with open fetch exposures to the north, northeast, east, southeast, and south were especially effected due to the rotation of Isabel's winds from north to south during her passage. Hundreds, if not thousands, of shore protection systems were damaged or destroyed. Many shorelines around the Bay which had no shore protection were moved 10 to 30 feet landward due to storm surge and waves. Shore reaches with properly designed and constructed headland breakwater systems incurred varying degrees of damage from none to several feet of cut at the adjacent base of the upland banks. This report documents the impact of Hurricane Isabel on four such systems in Chesapeake Bay. These sites are part of the Chesapeake Bay Breakwater Database.

The Chesapeake Bay Breakwater Database is being developed by personnel in the Virginia Institute of Marine Science's (VIMS) Shoreline Studies Program for the U.S. Army Corps of Engineers (COE) in order to:

1) document breakwater system performance around Chesapeake Bay relative to predictions
2) develop guidelines for breakwaters in sand limited and fetch limited systems such as estuaries, reservoirs, lakes and bays.

The Chesapeake Bay Breakwater Database Project has 42 sites (Figure 1). Although more Bay breakwater systems exist, the sites in the database were chosen because they were designed with regard to their site setting, impinging wave climate, and desired level of protection, *i.e.* the 25 yr or 50 yr. storm event. Many projects are older than 10 years, and all were impacted by Hurricane Isabel. Aquia Landing, Kingsmill, Van Dyke, and Yorktown were selected for detailed analysis of Isabel's impacts since the four sites were surveyed immediately prior to the storm. This provided an opportunity to physically determine shore changes that may result due to a major storm event that equaled the 1933 Hurricane in storm surge level. Hurricane of 1933 is the unofficial 100 yr event that the Federal Emergency Management Agency (FEMA) has, until this point, used for a reference datum in Chesapeake Bay.

These four sites were mapped using a real-time kinematic global positioning system before and after the storm. The data were analyzed for changes in sand levels in the beach and nearshore as well as for any upland or backshore impacts from the storm. To better understand these changes, low-level vertical aerial photography, taken before and after the storm, were georectified and the shorelines digitized. At all sites, the breakwaters performed well allowing little overall change to beach systems. Since these sites were designed for 25 and 50 year storms, all were "overtopped" with the combination of surge and wave runup. The beach/upland interface at the two high bank sites (Kingsmill and Van Dyke) incurred varying degrees of bank scarping, but no bank failure while the two low backshore sites (Aquia Landing and Yorktown) saw sand washed over into adjacent roadways. Beach planforms adjusted bayward under storm conditions but returned to pre-storm position.

2 Shore Management

When developing a framework for shoreline management, establishing clear objectives is necessary. In developing management plans, the following objectives should be given consideration:

- Prevention of loss of land and protection of upland improvements;
- Protection, maintenance, enhancement and/or creation of wetlands habitat both vegetated and non-vegetated;
- Management of upland runoff and groundwater flow through the maintenance of vegetated wetland fringes;
- Address potential secondary impacts for a selected strategy within the reach which may include impacts to downdrift shores through a reduction in the sand supply or the encroachment of structures onto subaqueous land and wetlands; and
- Providing access and/or creation of recreational opportunities such as beach areas.

These objectives must be assessed in the context of a shoreline reach. While all objectives should be considered, each one will not carry equal weight. In fact, satisfaction of all objectives for any given reach is not likely as some may be mutually exclusive. For instance, the type of shore (*i.e.* marsh, beach, bank) and ownership of downdrift property may alter management strategies as potential impacts are discussed in the design process.

Sites with a natural or environmental edge provide protection from coastal hazards such as storms. Wider beaches allow the waves to reduce in size before impacting the backshore. Vegetation serves to maintain the substrate during storm events. Low marshes may be completely overwashed by surge and mitigate the impact of waves while maintaining their structure since marsh is naturally more resistant to erosion than unconsolidated (*i.e.* sand) substrate. Dunes provide a natural "backstop" to waves before they impact the upland. In fact, Milligan *et al.* (2005) found that natural dunes at nine sites within the Chesapeake Bay estuarine system are naturally resilient and recover quickly. They protected upland structures from direct wave attack and mitigated any impact to upland banks. In developing management strategies, incorporating these features into shore protection in a cost effective manner enhances the overall system.

2.1 Modeling Coastal Structures in Chesapeake Bay

Shore management utilizes wind/wave modeling in order to assess wave climate on a reach basis. The computer models SMB and RCPWAVE are used. SMB generates a predicted wave height and period based on the effective fetch and offshore bathymetry of a site. RCPWAVE is a linear wave propagation model designed for engineering applications. This model, originally developed by the U.S. Army Corps of Engineers (Ebersole *et al.*, 1986), computes changes in wave characteristics that result naturally from refraction, shoaling, and diffraction over complex shoreface topography. To this fundamentally linear-theory-based model, routines have been added which employ wave bottom boundary layer theory to estimate wave energy dissipation due to bottom friction (Wright *et al.*, 1987). Over the years, a three step process has been developed (Hardaway *et al.,* 1995; Hardaway and Gunn, 1999a; Hardaway and Gunn, 1999b) to 1) assess the wind/wave climate using model SMB), 2) calculate the nearshore/nearfield wave refraction using RCPWAVE, (Ebersole, *et al.,* 1986), and 3) plot pocket beach shore planforms using Model SEB (Hsu *et al.*, 1989).

Utilizing the output from the RCPWAVE model as input to the Static Equilibrium Bay (SEB) model, the equilibrium planforms between structures can be determined. Beach planform calculations use the annual significant wind-generated wave approach direction and selected design storm conditions. This procedure was first developed by Silvester (1970) and later refined by Hsu *et al.* (1989) and Silvester and Hsu (1993). Their methods were developed along open-ocean, coastal embayments usually influenced by a unidirectional, significant annual wave field (Figure 2). In Chesapeake Bay, there often is a bimodal annual wind field that generates a bimodal wave climate that must be accounted for in beach planform design. This sometimes results in embayments with two tangential beach sections at any one time as beach planforms from one wind-generated wave field replaces or resides with another. Figure 3 shows the relationship of the three procedures in beach planform design that can be used for predicting bay shape.

The relationship between four specific headland breakwater system parameters were investigated by Hardaway *et al.* (1991) and Hardaway and Gunn (1991) for 35 breakwater embayments around Chesapeake Bay. Referring to Figure 3, these parameters include breakwater crest length, (LB), gap between breakwaters (GB), backshore beach width (Bm) and embayment indentation (Mb). The mid-bay backshore beach width and backshore elevation are important design parameters because they determine the size of the minimum protective beach zone in the headland breakwater system. This beach dimension often drives the bayward encroachment that is required for a particular shore protection design. Linear regression analyses were best for the relationship of Mb vs. GB with a correlation coefficient of 0.892. The ratio of these two parameters is about 1:1.65 and can be used as a general guide in siting the breakwater system for preliminary analysis. Then, the detailed bay shape using the SEB can be obtained. Stable relationships for Mb and GB are not valid for transitional bay/breakwater segments that interface the main headland breakwater system with adjacent shores. Numerous variations can occur depending on design goals and impinging wave climate.

Hardaway and Gunn (2000) found that for 14 breakwater sites around the Bay, the Mb vs. Gb ratio varies in range and average for bimodal and unidirectional wind/wave settings. For unidirectional sties, the range of Mb:Gb can be 1:1.4 to 1:2.5 with an average of 1:1.8. Aquia Landing and Yorktown have average Mb:Gb of 1:1.25 and 1:1.8, respectively. For bimodal sites Mb:Gb ratios vary from 1:1.0 to 1:1.7 with an average of 1:1.6. Kingsmill and Van Dyke have Mb:Gb ratios of 1:1.2 and 1:1.7, respectively.

2.2 Coastal Structures for Shore Management

Revetments are shoreline armoring systems that protect the base of eroding upland banks and usually are built across a graded slope (Figure 4). The dimensions of the revetment are dependent on bank conditions and design parameters such as storm surge and wave height. These parameters also determine the size of the rock required for long-term structural integrity. Generally, two layers of armor stone are laid over a bedding stone layer with filter cloth between the earth subgrade and bedding layer.

Breakwaters and sills are "free standing" structures designed to reduce wave action by attenuation, refraction, and diffraction before it reaches the upland region. A sill (Figure 5) has a lower crest, is closer to shore, and usually, is more continuous than larger breakwater units. Sills can be used in combination with larger breakwater units. Sills are installed with beach fill to create a substrate for establishing a marsh fringe.

Attached or headland breakwaters require beach fill in order to acquire long-term shoreline erosion control (Figure 6) since they are constructed in areas that are subject to more energetic conditions. Headland breakwaters can be used to accentuate existing shore features. The dimensions of a breakwater system are dependent on the desired degree of protection and potential impacts on littoral processes. Spurs are similar to breakwaters and sills in that they are "free standing" structures. The distinction is that spurs are attached to the shoreline or another structure; the unattached end of the spur acts as a breakwater by diffracting incoming waves

3 Site Information

3.1 Aquia Landing

Aquia Landing is a county-owned public beach on the Potomac River in Stafford County, Virginia (Figure 7). Prior to the project installation, the county beach was severely deteriorated with failing groins and washovers across a very low upland shore zone (Figure 8A). Long fetch exposures to the southeast of over 7 nautical miles (nm) and northeast of over 4 nm made the site vulnerable to storm damage. With partial funding from the Virginia Board on Conservation and Development of Public Beaches, a breakwater and beach fill project was installed in 1987. The project covered 1,200 ft of shoreline and consisted of 700 ft of stone revetment, four 110 ft headland breakwaters with 20,000 cy of beach fill bounded on each end by spurs (Figure 8B). Downdrift impacts were considered negligible due to low marsh composition and property ownership being the same as the breakwater system. The design utilized the shore morphology of the existing groin field to determine tangential beach orientation. The Static Equilibrium Bay (SEB) model was then applied to assess the predicted beach planforms for the headland breakwater systems (Hardaway *et al.*, 1993; Hardaway *et al.*, 1995; Hardaway and Gunn, 1999a; Hardaway and Gunn, 1999b; and Hardaway and Gunn, 2000). The pocket beach configurations have been stable since installation. The overall purpose of the project was to provide shore protection, create a recreational beach, and reduce beach hazards from deteriorating groins.

The design and performance of the site was analyzed by Linden *et al.* (1991). They found that during the three years after the installation of the project, the overall volume of beach material within the monitoring area had not changed. The wide, flat, shallow nearshore has allowed submerged aquatic vegetation (SAV) to expand at the site in the last 10 years (VIMS SAV website). This has likely helped maintain a stable nearshore during storm events.

3.2 Kingsmill

Kingsmill is located on the north shore of the James River in James City County, Virginia (Figure 7). It is a privately owned site that had chronic bank erosion and which has a long fetch exposure to the south of over 12 miles. The developer of the upscale residential community wanted shore erosion control with environmental edge (Figure 9A). A 2,800 ft breakwater system was installed in 1996. It consisted of six headland breakwaters ranging in size from 115 ft to 210 ft, a 110 ft low breakwater and a 170 ft revetment for boundary interfacing structures, beach fill, and wetlands plantings, all of which were designed for a 50-yr storm event (Figure 9B). The site's seventy foot high banks had little sand and posed potential upland drainage problems. The design routed upland drainage to an adjacent marsh, and low swales in the bank were used to allow storm water to diffuse through a vegetated beach fill. Beach fill was obtained from an upland borrow pit. The design utilized existing reach morphology and shore erosion patterns along with a hydrodynamic analysis which included SMB, RCPWAVE, and SEB models for a bimodal wave climate. The overall purpose of the project was to provide shore protection and habitat enhancement.

3.3 Van Dyke

Van Dyke is located on the south shore of the James River in Isle of Wight County, Virginia (Figure 7). It is a privately owned site that had severe erosion of its 50 ft banks due, in part, to it's exposure to a long fetch to the north of over 12 miles (Figure 10A). The site's bimodal wave climate and sand rich banks called for a breakwater system which utilized the bank sand for beach fill. Several factors were important considerations in the design; these were impacts to adjacent properties and the coordination of 15 property owners with varying degrees of support for and input to the project. However, the 2,300 ft project was installed in 1997. The system consisted of eight headland breakwaters ranging in size from 90 ft to 160 ft with open upriver boundary and a low short 50 ft interfacing breakwater and revetment downriver (Figure 10B). The project also included beach fill and wetlands plantings. Beach fill sand was selectively mined from adjacent 40 foot upland banks when they were graded. The overall purposes of the project were to provide shore protection and access to the James River.

3.4 Yorktown Public Beach

The Yorktown Public Beach is located on the south side of the York River in Yorktown, Virginia (Figure 7). It is approximately 1,200 feet in length. Historically, the beach was a product of erosion of nearby sandy upland banks and the littoral transport system. Over the years, the beaches along the waterfront began to narrow as the natural sediment supply was depleted by hardening of the updrift shorelines. Beaches were easily overwashed in storms, and they continued to erode (Figure 11A). The nearshore closest to the Colman Memorial Bridge is very deep as the river narrows. The channel under the bridge is naturally 90 ft deep. Downriver, the nearshore widens toward the National Park Service property.

In 1978, York County installed a riprap revetment along its picnic area shore to the east end of Yorktown. This area had been filled in Colonial days to expand the warehousing facilities at the Port of Yorktown. After a damaging storm in November 1985, a small breakwater with beach nourishment was installed in order to maintain a storm water outfall (Figure 11B). Subsequent renourishment occurred three years later.

In September 1994, York County installed Phase I of an offshore breakwater system which consisted of two shore-attached breakwaters (Figure 11C). These breakwaters, 140 and 120 feet in length, were coupled with 7,500 cubic yards of beach fill and plantings of *Spartina alterniflora* and *S. patens* in the lee of the structure. The pre-existing breakwater was modified to interface the system on the downstream end and the 120 foot breakwater has a falling crest elevation to encourage wave refraction, and a winged breakwater was designed to achieve a reasonable interface with the adjacent shore and reduce potential wave force impacts during northeasters. In May 1996, approximately 600 cubic yards of sand was dredged from under the Coleman Bridge as part of the bridge widening project. This sand was subsequently used as beach fill on Yorktown Beach.

In the fall/winter of 1998-1999, Phase II of the Shore Erosion Control Plan was implemented along the shoreline (Figure 11C). Two winged, headland breakwaters, 120 and 130 ft in length, were constructed downriver from the existing breakwaters. The small breakwater built in 1986 to stabilize the storm water outfall was removed in order to establish a better breakwater gap-to-bay indentation ratio for the new system. The storm water outfall pipe was relocated through one of the new breakwaters. In addition, approximately 10,000 cubic yards of sand was placed on the beach, and beach grasses were planted behind the structures.

Phase III of breakwater construction began in June 2000. The completed project included three new breakwaters, beach fill along the Yorktown waterfront, and a revetment. Since then, the wharf where the old post office sat was removed. Two smaller breakwaters, 80 and 85 ft in length were positioned at the far west of the reach. A larger winged, headland breakwater, 150 ft in crest length, was installed as well, and beach grasses were planted behind it. The existing revetment on the upriver end of the site was repaired and a new section was added toward the west. Along with the breakwater construction, a new walkway adjacent to the Water Street was added (Figure 11C).

Since then, an additional two breakwaters have been built on the upriver end of the site, and in 2005, three more were constructed upriver and one more downriver. History of the site, design guidelines, and performance of the Yorktown site over time has been documented in Milligan *et al.* (1996) and Milligan *et al.* (2005).

4 Hurricane Isabel

Hurricane Isabel made landfall along the southeast coast of North Carolina on September 18, 2003. At one time, the storm was a Category 5 on the Safir-Simpson scale. It had been downgraded to a Category 2 before it made landfall (Figure 12). By the time it impacted the Chesapeake Bay, it was a minimal Category 1. However, in addition to being in the “right-front” quadrant of the advancing hurricane, southeastern Virginia experienced east and east-southeast winds which are known to have the greatest potential to transport water into Chesapeake Bay and its Virginia tributaries. The hurricane impacted as far inland as Lake Erie.

The extent of coastal flooding during a storm depends largely on both the background astronomical tide and the surge generated by the storm's high winds and low atmospheric pressure. Together, surge and astronomical tide combine to form a "storm tide." Storm-tide flooding is maximized when the storm surge and a rising tide reach their peak at the same time. The SLOSH Model (Figure 13) depicts the maximum predicted surge levels around the Bay. However, it may have under-predicted certain areas, particularly up the rivers. Measured storm impacts would seem to indicate higher surges than then model predicted.

The hurricane of 1933, widely known as the "storm of the century" for Chesapeake Bay, generated a storm surge in Hampton Roads of 5.84 feet, more than a foot higher than the 4.76 ft storm surge recorded for Hurricane Isabel. Yet many long-time Tidewater residents say that the high-water marks left by Isabel equaled or exceeded those of the 1933 storm (Boon, 2003).

An analysis of sea-level records shows that Isabel's coastal flooding matched that of the August 1933 storm due to the long-term increase in sea level in Hampton Roads (Boon, 2003). Data from a tide monitoring station at Sewells Point show that sea level in Tidewater Virginia rose 1.35 feet between August 1933 and September 2003. Based on storm surge and astronomical tide, the 1933 hurricane storm surge exceeded Isabel's by more than a foot. Its surge also occurred at the beginning of spring tides while Isabel's surge occurred in the middle of a neap tide. However, the increase in sea level at Hampton Roads in the seventy years between the two storms was enough to boost Isabel's storm tide to within an inch and a half of the level experienced during the 1933 storm (Boon, 2003).

Additional storm data was obtained by an Acoustic Doppler Current Profiler (ADCP) which was deployed in 28 ft of water offshore of VIMS at Gloucester Point. The instrument provided a quantitative record of the hurricane's impact on lower Chesapeake Bay. Data from the ADCP showed that Isabel created a 7-foot storm tide topped by 6-foot waves. At the height of the storm, wave crests were passing over the instrument once every 5 seconds, and the storm was forcing the entire flow of the York River upstream at a rate of 2 knots. Because Isabel was so large, its winds, waves, and surge effected the Bay for an abnormally long time. The ADCP data showed that storm conditions persisted in the Bay for nearly 12 hours and that wave-driven currents were strong enough to mobilize bottom sediments even at the instrument’s depth, increasing water turbidity by a factor of two to three compared to fair-weather conditions (VIMS, 2003).

Weather data provided by instruments atop VIMS' Byrd Hall showed that maximum sustained winds on the campus reached 65 mph, with 90-mph gusts. The barometer bottomed out at 29.2 inches, with a rainfall accumulation of about 2.2 inches (VIMS, 2003).

Around the Bay, similar impacts were recorded by tide gauges (Figure 14). The location and records of five tide gauges indicate the widespread flooding that occurred due to the storm. In the lower Bay, the Sewells Point and Chesapeake Bay Bridge Tunnel gauges survived the storm and indicated a total water level of 8 ft and 7.5 ft above mean lower low water (MLLW) at the peak of the storm. This is about 5 ft above normal. Also of note, the tide was running higher than normal for the day before the storm and the two days after at both locations. In fact, on the day after the storm at Sewells Point, the lowest tide was higher than the predicted high tide of 2.5 ft.

The other three tide gauges were destroyed during the storm before the peak water level was reached (Figure 14). At Gloucester Point on the York River, the tide gauge stopped recording at 8.5 ft MLLW during the storm. Maximum measured stillwater level across the river at Yorktown was 8.6 ft MLLW with the trash line indicating the water plus waves was at 12.5 ft MLLW. That is a surge above the mean range (2.4 ft) of 6 ft with additional 4 ft waves. Kingsmill, on the James River, stopped recording at 6.5 ft MLLW. At this location, measured trash lines indicated that the maximum surge and wave level was about 12 ft MLLW or about 8 ft above the mean tide range.

The National Oceanic and Atmospheric Administration (NOAA) analyzed tide gauge data from all over the Chesapeake Bay. The report states that storm surge was generally lower and more variable in the lower Chesapeake Bay than those in the upper Chesapeake Bay. Also, surges at the open bay sites were lower than those located in the more restricted rivers (Hovis *et al.*, 2004). Their data show that the Hurricane Isabel tide levels exceeded the historical maximum water levels at two sites in the lower bay whose gauges were still in operation after the storm. These gauges were located at Lewisetta on the Potomac River and at the Chesapeake Bay Bridge Tunnel. The previous storm of record at these two sites was the Twin Northeasters in January/February 1998. The upper bay also was severely impacted by the storm. Tide gauges in Maryland at Cambridge, Annapolis, Tolchester, Baltimore and Chesapeake City all exceeded the historical maximum water levels during Hurricane Isabel. These stations are generally located at the headwaters of large rivers or bays where the storm's persistent winds pushed water into enclosed areas and held it there through a complete tidal cycle (Hovis *et al.*, 2004). At many sites, particularly in the upper Bay and rivers, the peak of the storm surge lagged behind high tide. At Sewells Point on the James River, the peak storm surge occurred about 2 hrs after predicted high tide while at Lewisetta on the lower Potomac river, the peak occurred about 3.5 hs after predicted high tide. The lag was even greater up the rivers and bay some even as much as 8 hours after predicted high tide. In fact, the maximum observed water level and peak storm surge in the upper Chesapeake Bay did not occur until the storm center had already reached Lake Erie (Hovis *et al.*, 2004).

5 Methods

5.1 Site Surveying

A shoreline and nearshore survey was performed at each breakwater site during the summer of 2003 serving as the pre-hurricane survey. After the passage of the storm, a post-storm survey was performed at each site. A Trimble 4700 Real-Time Kinematic Global Positioning System (RTK-GPS) was used to set site control and acquire shore data. The 4700 receiver utilizes dual-frequency, real-time technology to obtain centimeter accuracy in surveying applications. In addition, a Trimble 5600 Robotic Total Station was used to acquire data in the nearshore.

Base station benchmarks were pre-set at each site with a 2-hour occupation. These data were processed through the National Geodetic Survey's On-line Positioning User Service (OPUS) (http://www.ngs.noaa.gov/OPUS/). All the survey data were based on these benchmarks. In addition, 3-minute occupations were taken at secondary benchmarks in order to determine survey error. After the hurricane, many benchmarks needed to be reset. The horizontal datum is UTM, Zone 18 North, NAD83, international feet. The vertical datum is feet MLLW, geoid99, as determined from nearby benchmarks publishing both NAVD88 and MLLW for the 1960-1978 tidal epoch (http://www.co-ops.nos.noaa.gov/bench_mark.shtml?region=va).

Generally, the surveys included the following elements:

1. Dimensions of the project structures;
2. Mean High Water (MHW) and Mean Low Water (MLW); survey extends to approximately the -3 ft MLW contour;
3. Base of bank, mid-bank and top of bank, where appropriate and possible.

Survey dates and site length are as follows:

Aquia Landing	12 Aug 2003	30 Sept 2003	1,100 ft
Kingsmill	21 Aug 2003	6 Oct 2003	2,300 ft
Van Dyke	20 Aug 2003	21 Oct 2003	2,200 ft
Yorktown	June 2003	25 Sep 2003	1,800 ft

5.2 Storm Photo Geo-Referencing and Mosaicking

Recent color aerial photography was acquired by Shoreline Studies Program to help estimate, observe, and analyze shoreline changes before and after Hurricane Isabel impacted the breakwater sites on September 18, 2003. The images were scanned as tiff files at 600 dpi. ESRI ArcMap GIS (www.esri.com) software was used to georeference the images for Van Dyke, Aquia Landing, Elms Beach, and Kingsmill. The reference mosaic, the 2002 Digital Orthophotos from the Virginia Base Mapping Program (VBMP), is divided into a series of orthophoto tiles and is stored in a Virginia south, state plane projection, in feet. The aerial photo tiles from VBMP for each site were mosaicked and re-projected to a UTM zone 18 North, NAD83 projection, in meters.

Rectifying requires the use of ground control points to register the aerial photography to the reference images. Ground control points are points that mark features found in common on both the reference images and on the aerial photographs that are being georeferenced. Control points were distributed evenly to maintain an accurate registration without excessive amounts of warp and twist in the images. In addition, where possible, enough control points were placed within the area of interest, the shoreline and the breakwaters, to ensure accurate registration in these key areas. This can be challenging in areas with little development. Good examples of control points are permanent features such as manmade objects and stable natural landmarks. The standard in this project was to achieve a root mean square (RMS) error under six for each aerial photo.

Georeferencing was done by using the Georeferencing Tool in ArcMap. First the reference image and the scanned aerial photograph are roughly aligned so that common points can be identified. Then, with the aid of the Georeferencing tool, ground control points are added until the overall RMS error is less than six and the location of the aerial photograph closely matches the location of the reference image. When an acceptable correspondence is achieved, the aerial photograph is saved as a rectified image. All the rectified images were then mosaicked using the mosaic tool in ERDAS Imagine.

6 Results

6.1 Aquia

6.1.1 Isabel Hydrodynamic

Aquia Landing's east-facing shoreline has a nearly north-south orientation. Winds from the north, northeast, east, southeast, and southerly directions will impact this beach. Storm surge measurements at Colonial Beach stopped at about 6:00 p.m. on September 18, 2003 when the pier the gauge was attached to was destroyed (Figure 14). The tidal elevation had reached about +5.5 ft MLLW and was still climbing. Normal high tide at Colonial Beach is about 4 hours ahead of Aquia Creek. Mean tide range is 1.6 ft in Colonial Beach and 1.3 ft at Aquia Landing. The closest operating wind gauge during Isabel was at Lewisetta some 38 miles southeast down the Potomac River. On the day of the storm, northeasterly winds were increasing and sustained at 26 mph at about noon. By 4:00 p.m., they had reached 43 mph and were arriving from the east-northeast. At this time, a storm surge of about +2.2 ft MLLW may have been impacting Aquia's shoreline. As the wind increased, it's direction slowly shifted to the east then southeast resulting in a window of significant wind/wave impacts occurring between 6:00 p.m. and 10:00 p.m. as the surge rose. The peak sustained winds (53 mph from the east-southeast) occurred about 8:00 p.m. on September 18th. However, interpolated peak surge at Aquia was about 10:00 p.m. when sustained wind speeds had dropped to 43 mph from the southeast at Lewisetta. Maximum still-water level at Aquia Landing was surveyed at about +8.6 ft MLLW.

6.1.2 Physical Impacts

The survey baseline at Aquia Landing runs along the top of a Jersey wall that separates the public beach from the adjacent access road. The road is about 2 ft lower than the beach at the junction of the wall. Aerial imagery pre- and post-Isabel show that enough sand, about 1 ft, overwashed the wall to completely cover the access road (Figure 15). The shift in shoreline position was mostly landward after Isabel. Typical bay beach profiles (Figure 16) show a cut and fill scenario while the tombolo beach in the lee of each breakwater unit were sheared down about 0.5 feet. Little or no scour existed in front of the breakwaters while slight infilling occurred in each embayment. A slight increase in elevation was measured on the river side of the wall as the sand was moved up and over except where one scour hole occurred at the beach/wall junction. In addition, a reduction in vegetation in the lee of each breakwater occurred (Figure 17). The walkover to the beach was destroyed, and the bathhouse was flooded by the 8.6 ft MLLW surge that covered everything at the site.

The overall change in topography of the site is shown in Figure 18. The yellow and orange areas on the isopach map indicate decreases in elevation of -0.5 ft and -1.0 ft, respectively (Figure 18C). These areas occur in front and in the lee of each breakwater and along the beach berm zone of each embayment. Overall slight increases in sand elevation are shown in purple (+0.5 ft change) which occur intermittently along the backshore of each embayment and green (+1.0 ft change) which occur mostly along the very nearshore of each bay. No extreme changes (>1 ft) were measured in topography indicating the overall stability of the breakwater system.

6.2 Kingsmill

6.2.1 Isabel Hydrodynamics

The Kingsmill south-facing shoreline is oriented approximately east-west allowing wind/waves from the southeast, south, and southwest to impact the site. Water levels were measured at Kingsmill by a tide gauge until about 2:30 p.m. on September 18, 2003 (Figure 14). During the storm, the gauge was damaged, and the last reading was about 6.6 ft MLLW while tide was still rising. Wind and water level data also were measured at Sewells Point which is about 23 nautical miles downriver from the site. Wind speeds at Sewells Point exceeded 45 mph and remained so from 9:30 a.m. to about 5:00 p.m., and they reached sustained speeds of over 50 mph while water levels peaked at about 4 p.m. Kingsmill is located about halfway between Richmond and Norfolk, both of which have long-term wind monitoring stations. Wind data from Richmond shows more persistent winds from the north and northeast through the day on September 18 while Norfolk wind data showed winds more persistent from the east-northeast before they turned east then south. The combination of storm surge and southerly wind/wave climate, as indicated by the survey as the top of the bank scarping, resulted in water levels greater than +10.2 ft MLLW.

6.2.2 Physical Impacts

Pre- and post-Isabel aerial imagery of the site show slight changes in shore position (Figure 19). Each tombolo apex had a tendency to shift upriver. Measurable base of bank recession occurred along much of the project, but it was particularly prevalent adjacent to each embayment. These changes are illustrated in the typical bay and breakwater profiles in Figure 20. The combination of storm surge and wave runup limits were measured in the field and are shown for each typical profile at just over 10 ft MLLW. This was a significant event for the site, yet overall damage was minimized by the heavily vegetated backshore/base of bank (Figure 21). Post-Isabel recovery is shown in Figure 19; the beach planforms have returned to approximately their pre-storm poitions.

Topographic changes along the site between BW3 and BW7 are shown in Figure 22. The isopach map that indicates a general pattern of reduction in elevation occurred along the beach, backshore, base of bank and around each breakwater unit. Most increases in elevation were in the nearshore and in small pockets in the lee of each breakwater unit. The most severe scour occurred along the base of the bank (BOB) between BW5 and BW6. However, the damage did not endanger the integrity of the bank face. No slumping or failure was noted or has occurred since. Just upriver, extensive damage (more than $3 million) occurred at the adjacent marina which only had a timber pile breakwater for protection.

6.3 Van Dyke

6.3.1 Isabel Hydrodynamics

Once again, Sewells Point is the closet data station to this site; both wind and tide data are available through the entire storm event. Normal tidal lag for MHW between Sewells Point and the site is about 1 hr and 20 minutes. Although Sewells Point is the closest climatic station to the site, every indication is that conditions were more intense at Van Dyke than Kingsmill as evidenced by the severity of bank cut and limit of runup. Data from Richmond indicated that winds were more from the north and northeast throughout the day of September 18 while Norfolk data showed winds more persistent from the east-northeast before turning east then south. As a result of Van Dyke's north and northeast-facing shoreline, winds from the northwest, north, and northeast impacted this site. Wind speeds at Sewells Point got above 45 mph and remained so from 9:30 a.m. to about 5:00 p.m., and they reached sustained speeds of over 50 mph. The wind direction at 9:30 am was east-northeast and turned east by noon and southeast by 5:00 p.m. By interpolating between Richmond and Sewells Point, it would appear that Van Dyke had more of a northeast wind than indicated by the Sewells Point data.

Storm surge at Van Dyke at 9:30 a.m. was +4.8 ft MLLW, about +6.0 ft by noon, and over 8 ft MLLW by 5:00 p.m. The storm surge and northeast wind/wave climate combined to produce significant impacts to the site with wave runup measured to over 10 ft MLLW. The twin northeasters of 1998 produced storm surge of 7.5 ft over two tidal cycles but with less sustained winds, peaking around 35 mph. Wave modeling at the site (Hardaway and Gunn, 1999) predicts that for an 8 foot surge and 70 mph wind from the northeast, a 3.5 foot breaking wave would be produced.

6.3.2 Physical Impacts

Aerial imagery pre- and post-Isabel shows mostly landward shifts in the positions of both the shoreline and base of bank (Figure 23). Reduction in tombolo size are seen behind BW3, BW4, BW5, BW6 and also BW7 which had the narrowest attachment before the storm. The adjacent base of bank (BOB) along these structures also receded. Significant BOB recession also occurred in Bay A. General BOB stability is seen between BW2 and BW4 as well as between BW7 and BW8. These trends are shown in typical profiles for select bays and breakwaters (Figure 24). The combination of storm surge and wave height exceeded 11 ft MLLW, about 3 feet higher than project design. Post-storm recovery shows the shore planforms have returned to approximately their pre-storm configuration (Figure 23).

Ground photos taken before and after Hurricane Isabel show the extent of the upland bank scarping by the combination of storm surge and wave impacts (Figure 25). The retreat of the BOB was generally more severe in the embayments than behind the breakwaters and associated tombolos. Also, BOB impacts were minimal where the interface between the backshore and BOB had a less steep gradient. This occurred where the banks had been mined for sand, at Bay B and Bay G.

The overall change in topography at this site is seen in Figure 26. Negative topographic changes are evident at each tombolo and around and in front of BW5, BW6 and BW7. Severe land reduction occurs along the aforementioned BOB and along the top of the downriver revetment. Consequent increases or no change in topography are generally greater in the nearshore areas as indicated by the pink patterns (0 ft<change<1 ft).

6.4 Yorktown

6.4.1 Isabel Hydrodynamics

Yorktown is located across the York River from VIMS where NOAA maintains the Gloucester Point tide gauge (Figure 14). During Isabel the gauge stopped at about 2:30 p.m. with a reading of about +8.3 ft. MLLW as the tide was still rising. Wind speed measurements at VIMS provided by instruments atop VIMS' Byrd Hall showed that maximum sustained winds on the campus reached 65 mph, with 90-mph gusts. The barometer bottomed out at 29.2 inches, with a rainfall accumulation of about 2.2 inches. At the height of the storm, VIMS' Acoustic Doppler Current Profiler (ADCP) measured what might be considered a "deepwater" wave of 6 ft with a 5 second period. Still-water level at Yorktown was measured at 8.6 ft MLLW (mean tide range is 2.4 ft), and the combination of maximum storm surge and wave runup was measured at about 12.5 ft MLLW. One could infer that there could have been a 4 foot or greater wave breaking across the breakwater system and into the adjacent infrastructure.

6.4.2 Physical Impacts

Pre- and post-Isabel low level aerial imagery show a narrowing of each tombolo and a landward shift of sand behind each breakwater unit (Figure 27). The shoreline position in the two middle and largest embayments showed only slight changes after the storm. Typical profiles show cross-sectional changes as a basic cut and fill in the embayments (Figure 28). Shearing occurred across the top of the tombolos as well. Some sand was lost to the offshore after the storm but the County filled the beach to it's pre-storm profile shortly after the hurricane. Post-storm recovery about one year later shows shore planforms to have returned to their pre-storm position. A noticeable shore advance is seen in Bay C.

Sand was carried into the adjacent street but recent granite block "backstops" helped reduce this tendency. These blocks measuring about 1 ft square, 5 feet long, and weighing about 1 ton were easily shifted around by the storm waves. Several areas of scour occurred along the backshore/sidewalk/road juncture (Figure 29), but post storm clean up and added fill restored the public beach to use by late October 2003. The businesses along the waterfront were severely impacted, and it took several months for their rehabilitation due to water damage, but they are presently operating. Figure 30 shows a low backshore along Water Street in Yorktown as well as the storm wrack lines. At Colonial National Historical Park, just downriver from Yorktown, small rocks from the revetment along the shoreline were scattered on the road, and the adjacent upland bank was severely scarped.

7 Discussion

7.1 Aquia

Aquia Landing was the least impacted by Hurricane Isabel of the four sites discussed in this report. It had the least storm surge and it was not directly impacted by wave attack. Nevertheless, the storm impacts were enough to carry sand into the access road due to the low backshore and the absence of an upland bank. However, no significant infrastructure was damaged at the site. Overall, this site faired very well with little or no impact.

Just downriver at two other sites which had no shore protection system, significant change occurred (Figure 31). Dahlgren is on the south side of the Potomac River just downriver from the Route 301 Potomac River Bridge. Its bank was eroded 15-20 ft threatening upland infrastructure (Figure 32). On the north side of the Potomac River, Lenhart is slated for development. During the storm, its bank retreated 10-15 ft due to the storm (Figure 33).

7.2 Kingsmill

At Kingsmill, the very high banks and high end infrastructure posed a significant problem for long-term shore protection. The design had considered these factors so performance expectations were high. The headland breakwater system performed beyond expectations. The storm surge and wave action overtopped the system but impacted a heavily vegetated backshore/base of bank area causing minimal bank scarping which posed no threat to the integrity of the graded bank face.

Just up the James River along the National Park Service's Colonial Parkway, significant retreat occurred to the unprotected bank (Figure 34). The higher bank at the Confederate Fort had scarping leading to the loss of trees along the waterfront. Farther upriver in the open area adjacent to the Parkway, in areas where the bank was not sloped, scarping and retreat occurred. However, where the upland is graded to water interface, only minor scarping occurred.

7.3 Van Dyke

Hurricane Isabel exceeded the design conditions at the site, but it is difficult to accurately quantify its hydrodynamic forces. All of the piers along the shore sustained significant damage, and although the base of the bank was cut along most of the site, no banks failed or incurred significant damage. The banks will be regraded and a wider backshore will provide a larger buffer between the banks and storm waves once the vegetation is restored. No significant alteration in beach planform or loss of sand from the system occurred. The breakwater system is stable.

Both Kingsmill and Van Dyke have high graded banks adjacent to the breakwater/beach system which interface at about +7 ft MLLW for each site which is the elevation of a 50 year return interval storm. During Hurricane Isabel, the combination of storm surge and wave height impacted the banks to over +10 ft MLLW at both sites. Kingsmill had a much denser vegetated backshore and was able to withstand wave attack better than areas of Van Dyke. The Van Dyke site is more exposed due to its orientation causing bank cutting in the embayments in front of the steeper bank areas. Areas with a gentler grade at the beach/base of bank interface had little or no bank scarping. Isabel exceeded the design level for each site.

Near Van Dyke on the James River, other sites did not fair as well. Just downriver from Van Dyke, a revetment at the east end of the site was overtopped by the storm surge and waves (Figure 35). No erosion occurred of the graded bank just upriver from the revetment where the beach is wide behind a headland breakwater. The revetment crest elevation is +8 ft MLLW. Mogarts Beach, a few miles downriver on the James, suffered severe erosion of the beach and bank, a loss of over 20 ft in places, such that a road is now threatened (Figure 36). The narrow beach and low revetment offered little protection to the shoreline.

7.4 Yorktown

The waterfront at Yorktown was severely impacted by Hurricane Isabel. The low backshore and adjacent low bank allowed the storm surge to inundate the structures protected by the project. However, the wave action was significantly reduced by the public beach's breakwater system which may have spared the structural integrity of the buildings located along Water Street. This system experienced sand losses and local scour but maintained its overall integrity and performed above expectations. The system was designed for a 50 year event and sustained what many consider a 100 year event in this part of the Bay.

Approximately 1.5 miles downriver from the Coleman Memorial Bridge, also on the south side of the York River, the National Park Service maintains the Moorehouse. Their 1,600 ft of shore has a general west-northwest to east-southeast orientation and is exposed to the Chesapeake Bay from the northeast. Water depths are relatively shallow with the 12 ft contour approximately 800 ft offshore, and waters deeper than 36 ft is 2,000 ft offshore. The upland shore areas have 30 to 40-foot mostly vertical cliffs with interspersed ravines. The elevation of the revetment is about +6 ft MLLW. Significant scarping occurred above the revetment and along the section of shore that was unprotected with bank recession of about 5 to 10 ft (Figure 37).

8 Conclusions

The four breakwater sites assessed for this report performed very well under the direct impacts of high water and waves produced by Hurricane Isabel. All systems were 2 to 4 ft under water with an additional 2 to 3 foot waves breaking across what was the surf zone during the storm. Aquia and Yorktown were completely overtopped as waves attenuated across the breakwater system and impacted the low backshore and adjacent upland. Maintenance at each site only required returning the sand to the beach from the adjacent road. Yorktown required about 1,000 cy of sand to fill in the scour holes along the backshore/side walk intersection.

The Kingsmill and Van Dyke breakwaters systems had the task of reducing storm wave attack against high upland banks and preventing catastrophic scour and bank failure. Each system performed well, and the results indicate that a less steep gradient between backshore and the bank face greatly reduced the potential for bank scour. Also, a heavily vegetated backshore/base of bank interface may greatly reduce bank scour. The only post-storm maintenance to the banks that had to be performed was regrading several areas at Van Dyke. No additional sand fill was required at either site.

There is always a discussion of costs vs. benefits for any type of shore protection. The fact is that well built stone walls at +8 ft MLLW were overtopped and the adjacent upland scarped. The advantage or desirable element with headland breakwaters is that comparable or better shore protection is attained with a stable beach system that remains intact after the event. Higher breakwaters and more sand would give more protection, but at what cost?

The significance of the hurricane and the minor damages occurring at each site shows that headland breakwater systems offer effective shore protection with the benefits of beach and dune habitat. The post storm recovery is also important and shows the durability of the designed beach planforms.

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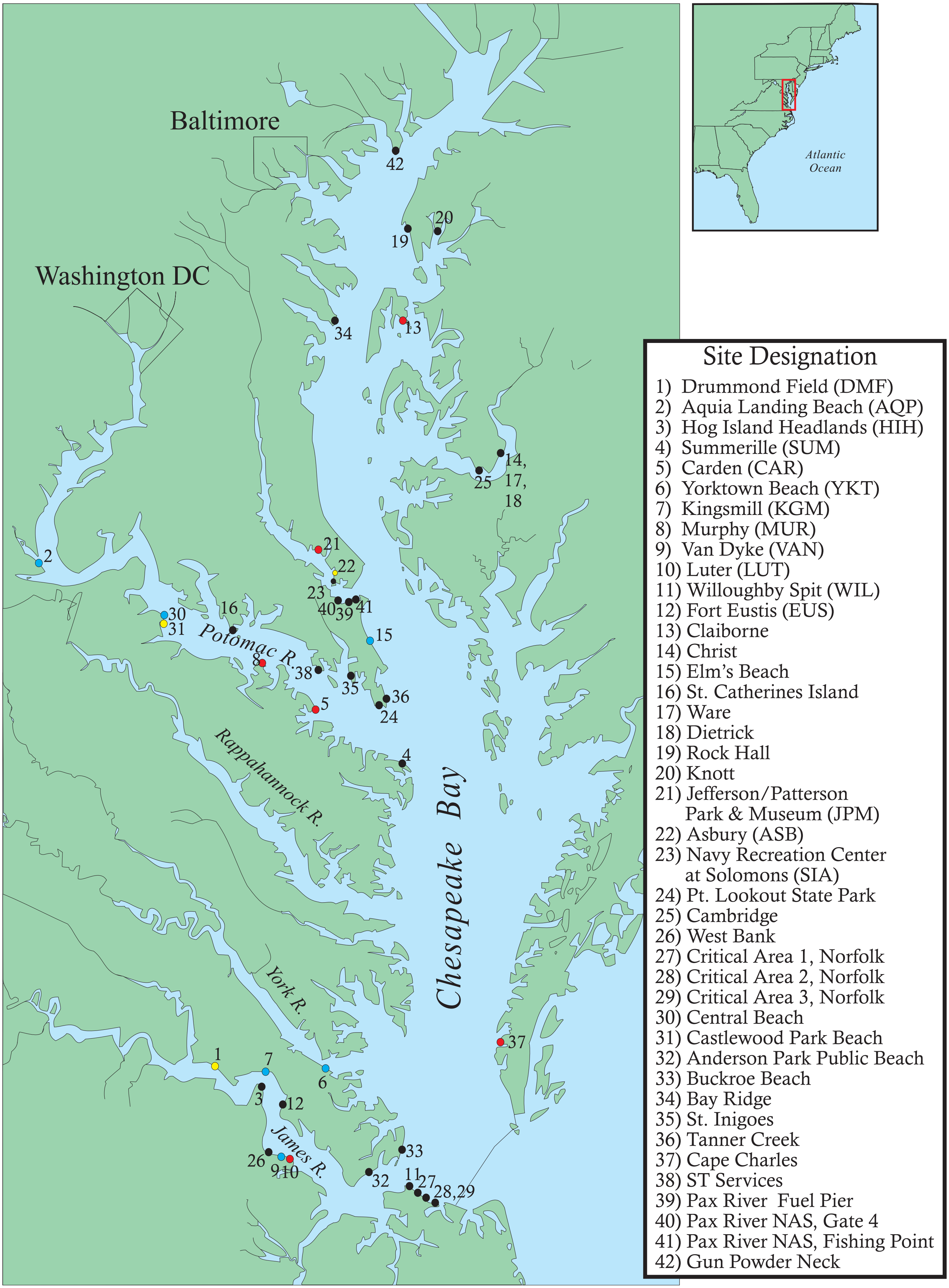


Figure 1. Location of breakwater sites throughout Chesapeake Bay. 2003 survey sites are shown in yellow; Post Isabel survey sites are shown in blue; and 2004 survey sites are shown in red.

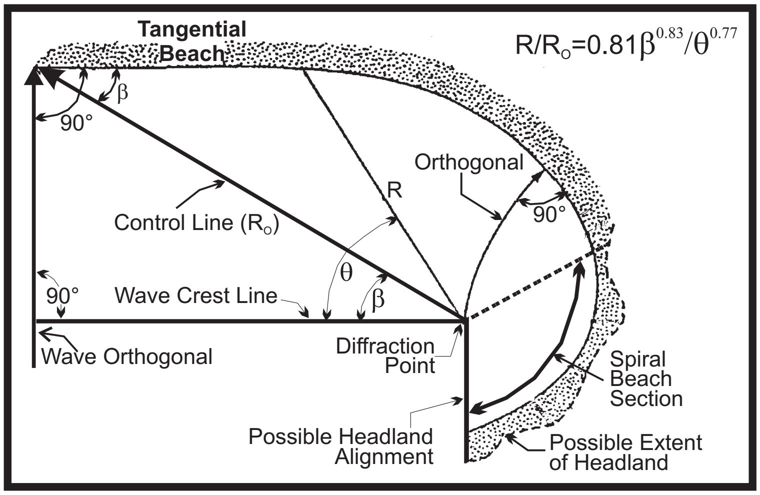


Figure 2. Parameters of the Static Equilibrium Bay (after Hsu *et al*., 1989).

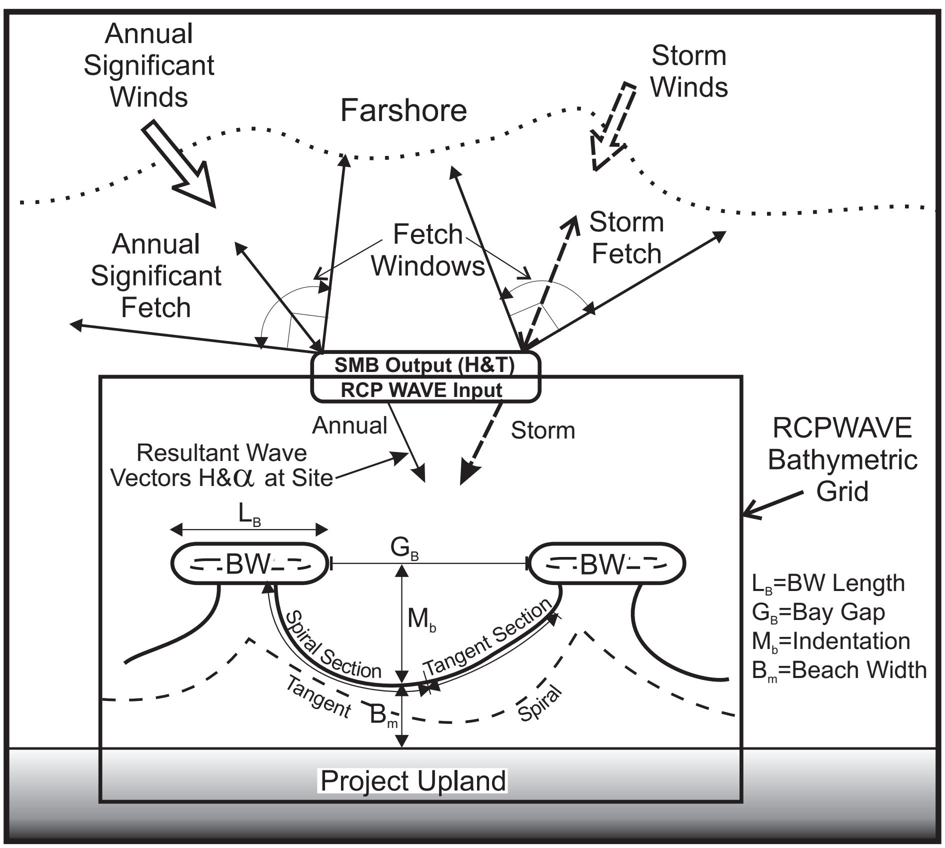


Figure 3. Parameters related to wind/wave generation (SMB), nearshore wave refraction (RCPWAVE), and beach planform prediction (SEB).

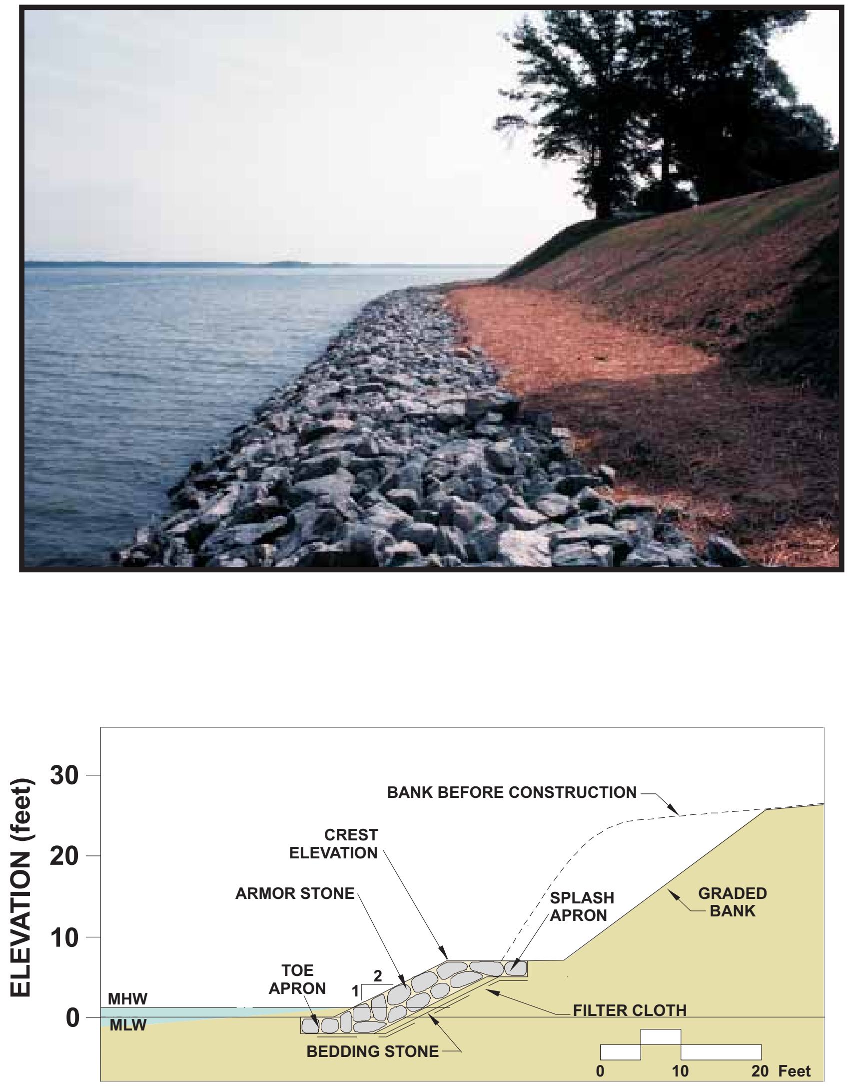


Figure 4. Stone revetment shortly after construction on the Potomac River, Virginia; and cross-section of elements necessary for proper stone revetment design. There are usually two layers of armor stone over a bedding stone layer with filter cloth between the earth subgrade and bedding layer. Armor size is dependent on the design wave height which is determined from an analysis of wave climate for each project site (Hardaway and Byrne, 1999).

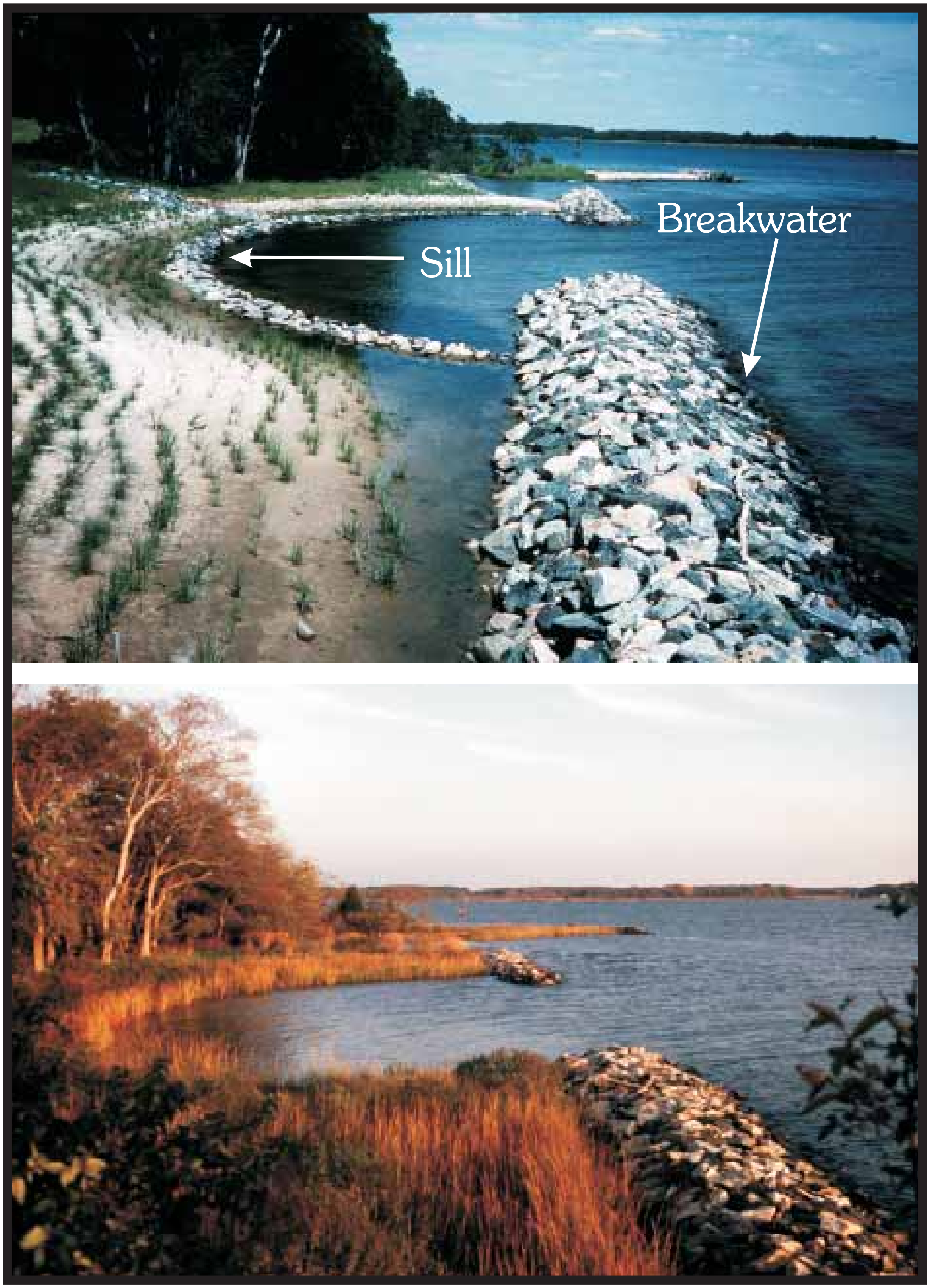


Figure 5. Stone sill connecting breakwaters with sand fill and marsh implantation on Choptank River, Talbot County, Maryland just after construction and 5 years post-construction (Hardaway and Byrne, 1999).

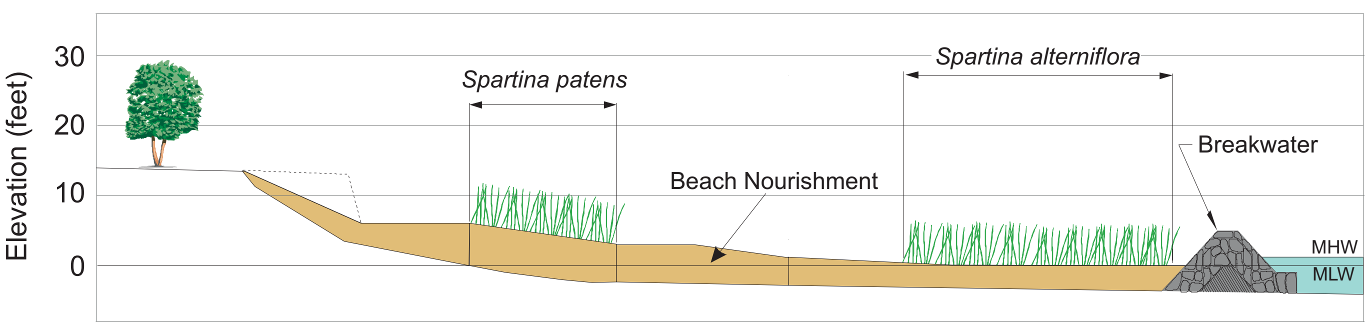


Figure 6. Breakwater system on Patuxent River in Calvert County, Maryland and a typical breakwater cross-section.

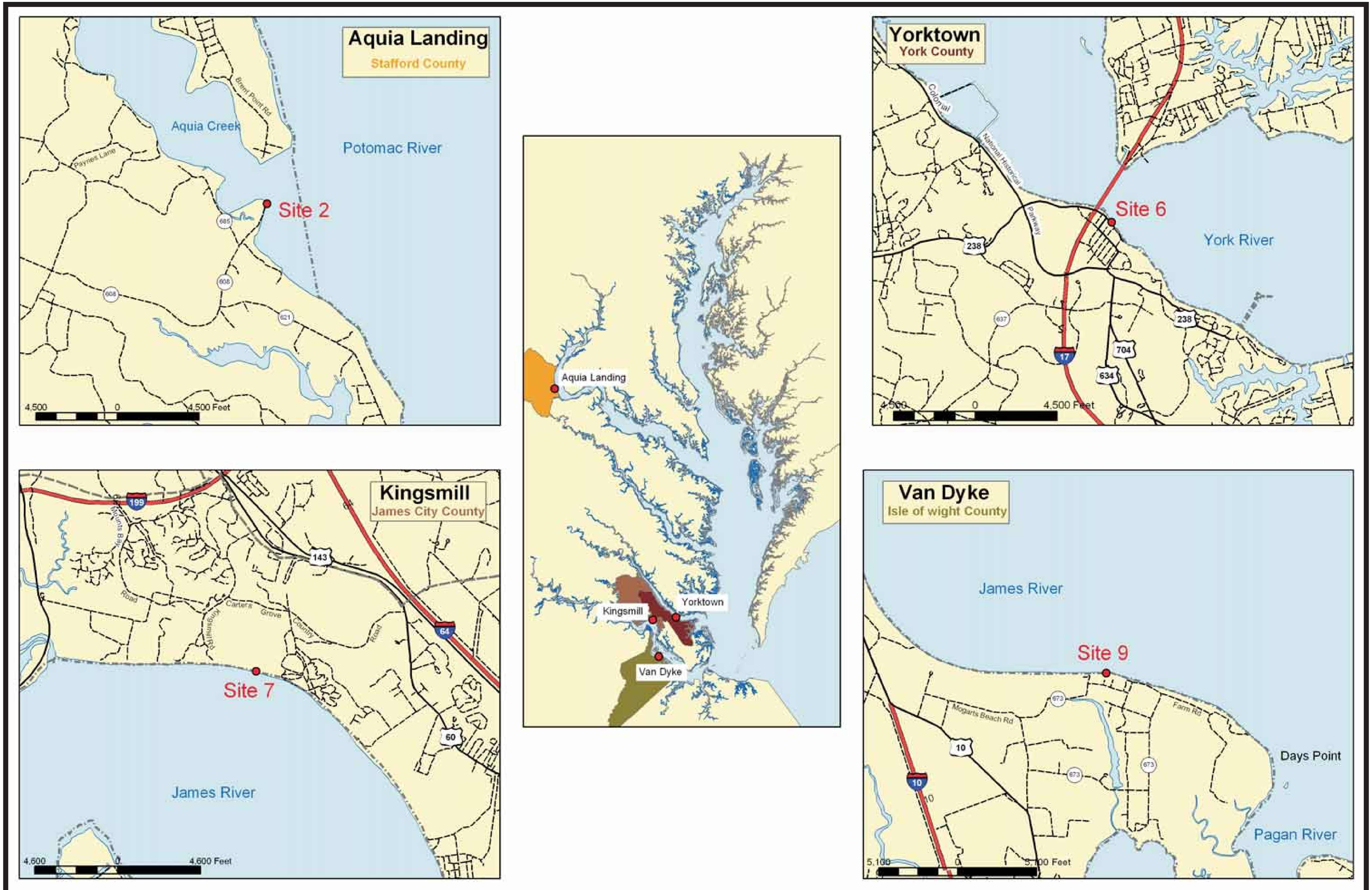


Figure 7. Location of the surveyed breakwater sites analyzed for this report.

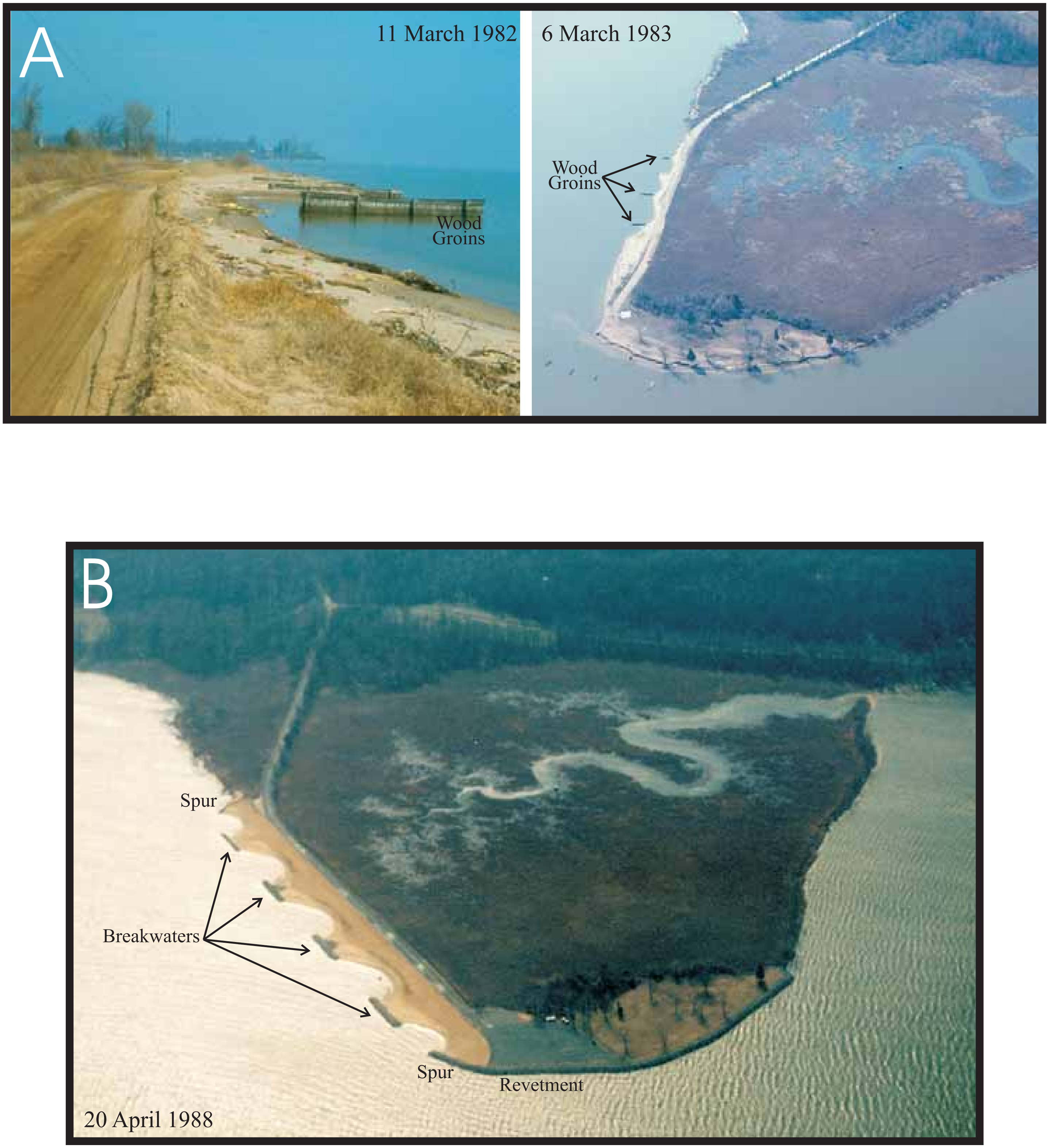


Figure 8. Photos of Aquia Landing A) before installation of breakwaters on the ground and aerially, and B) after installation of breakwaters.

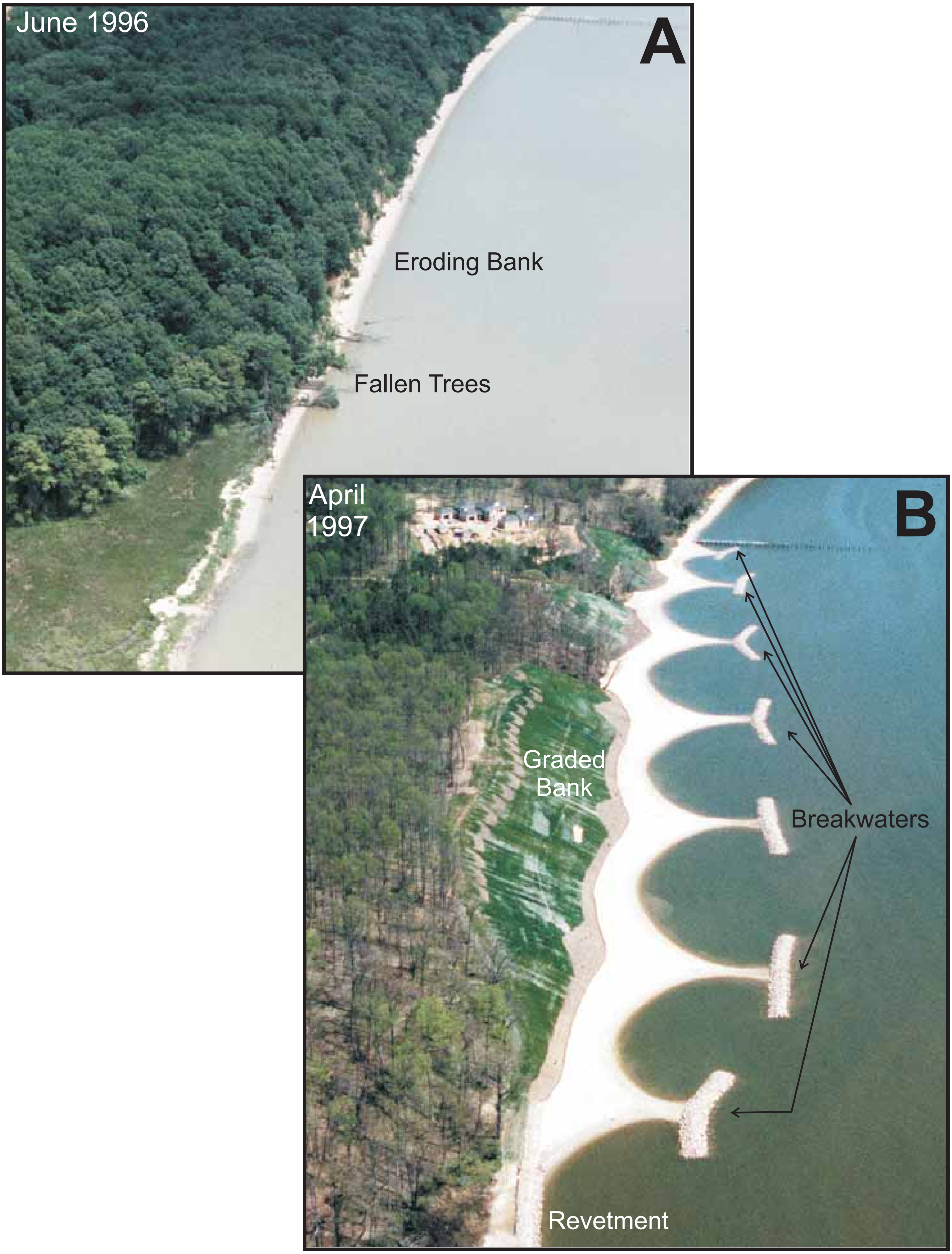


Figure 9. Photo of Kingsmill A) before installation and B) after installation.

Figure 10. Non-rectified aerial photography of Van Dyke A) before installation and B) after installation.

Figure 11. Aerial photos of Yorktown A) before installation of any shore management structures, B) after installation of a revetment and small breakwater, and C) after Phase III breakwater construction.

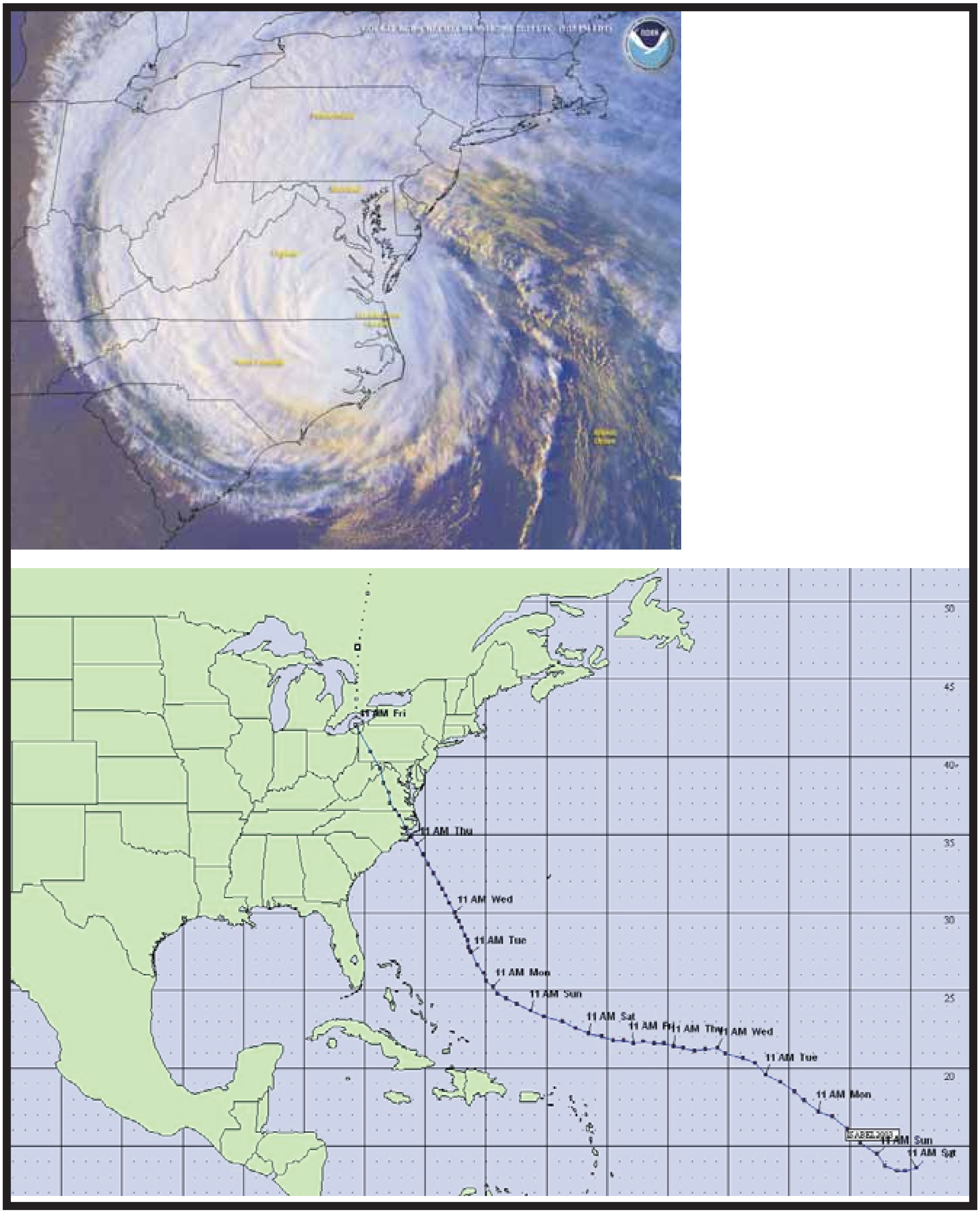


Figure 12. Hurricane Isabel photo at landfall and storm track from the National Hurricane Center.

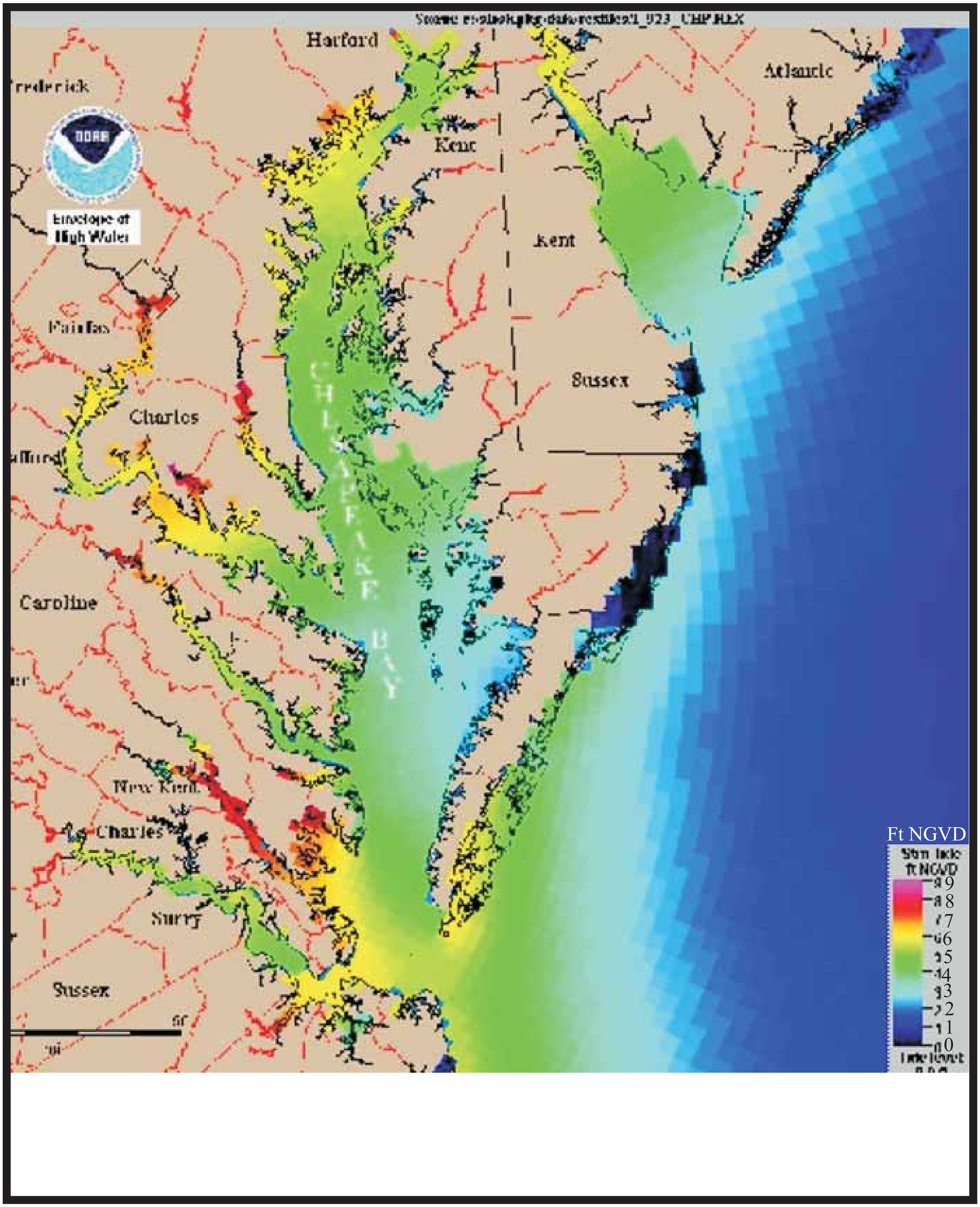
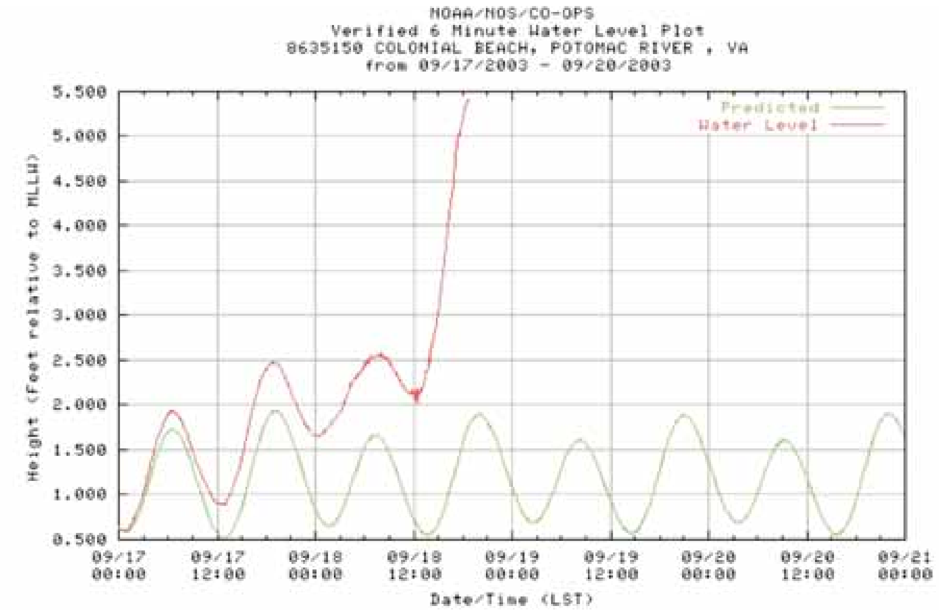
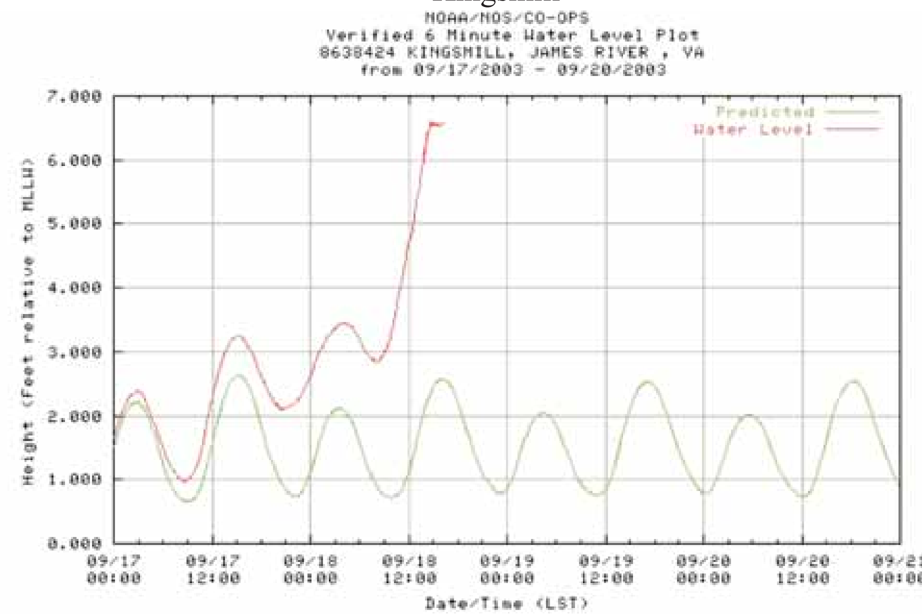


Figure 13. NOAA's slosh model storm surge prediction graphic.

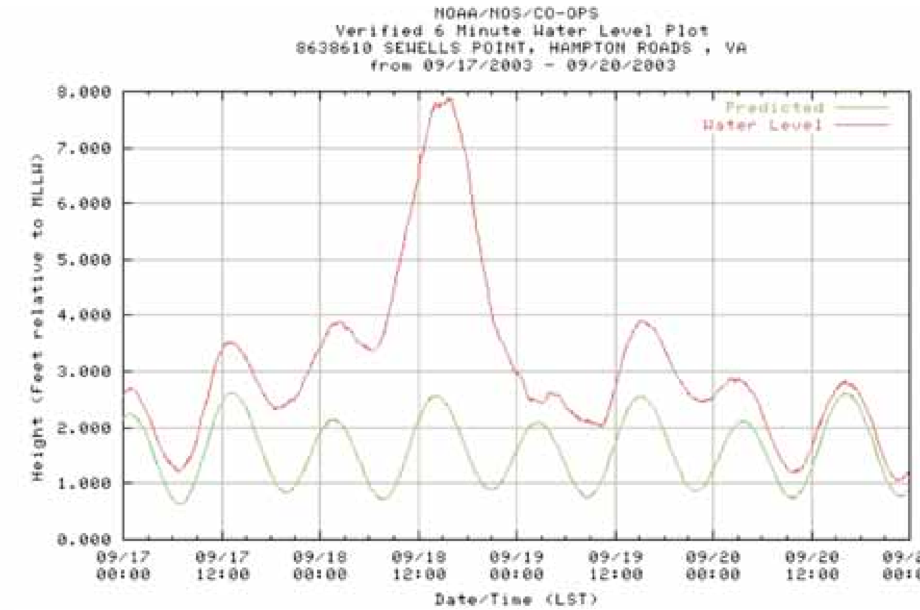
Colonial Beach



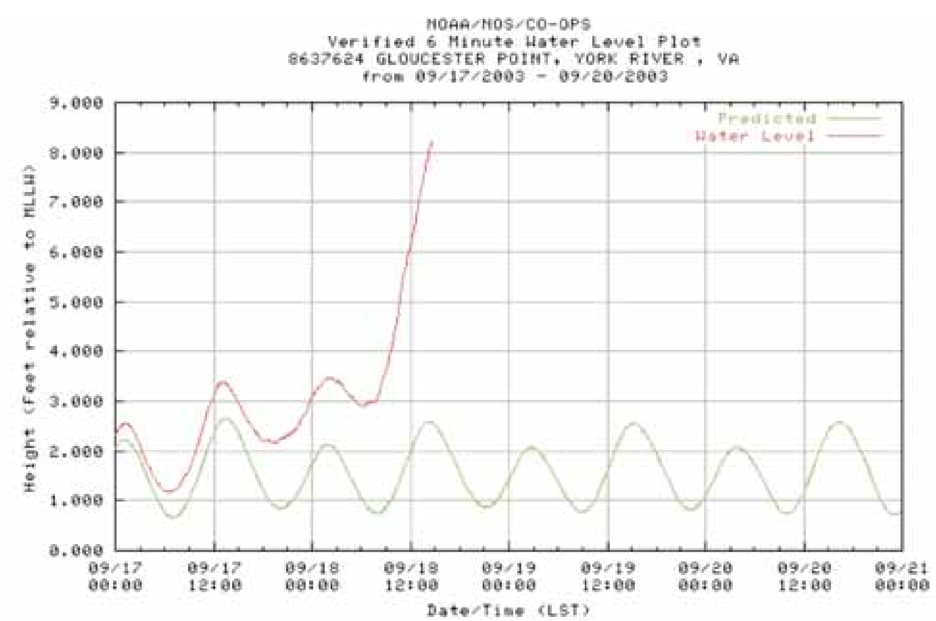
Kingsmill



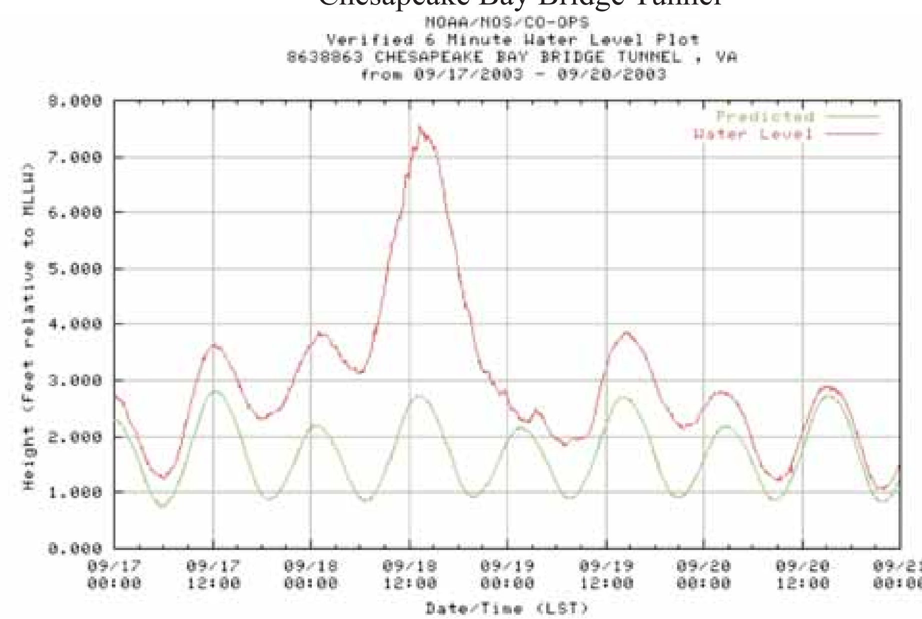
Sewells Point



Gloucester Point



Chesapeake Bay Bridge Tunnel



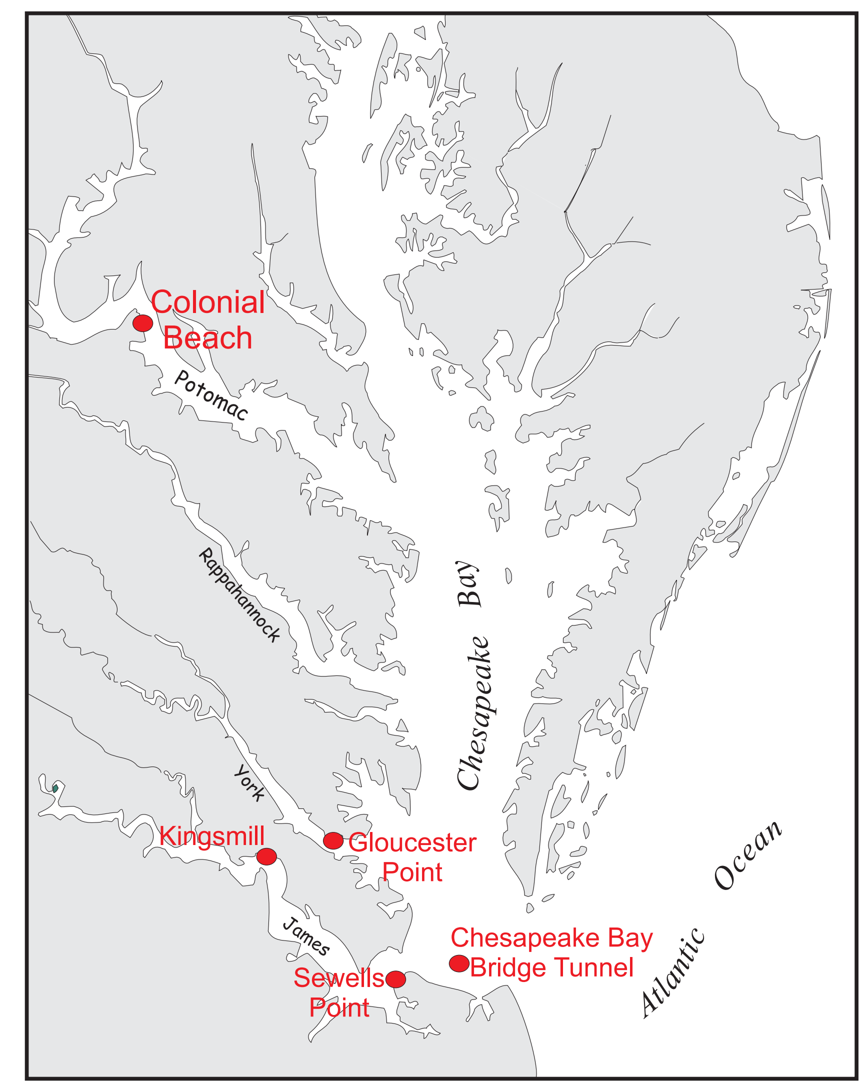


Figure 14. Verified water levels at wave gauges around Chesapeake Bay during the storm and approximate gauge location. From the NOAA website (http://www.co-ops.nos.noaa.gov/).

Figure 15. Aquia Landing low-level pre- and post-Hurricane Isabel ortho-rectified aerial photos.

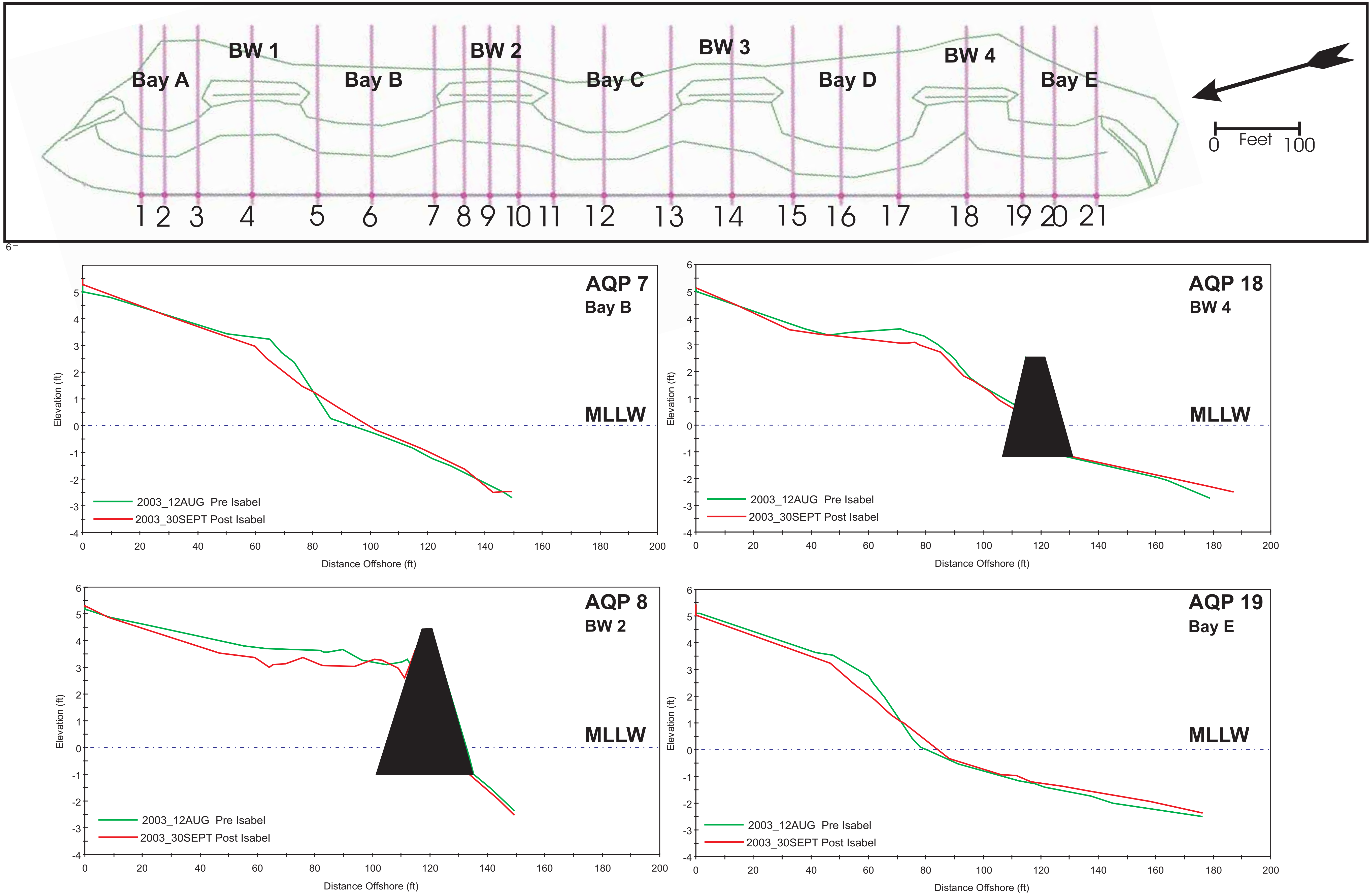
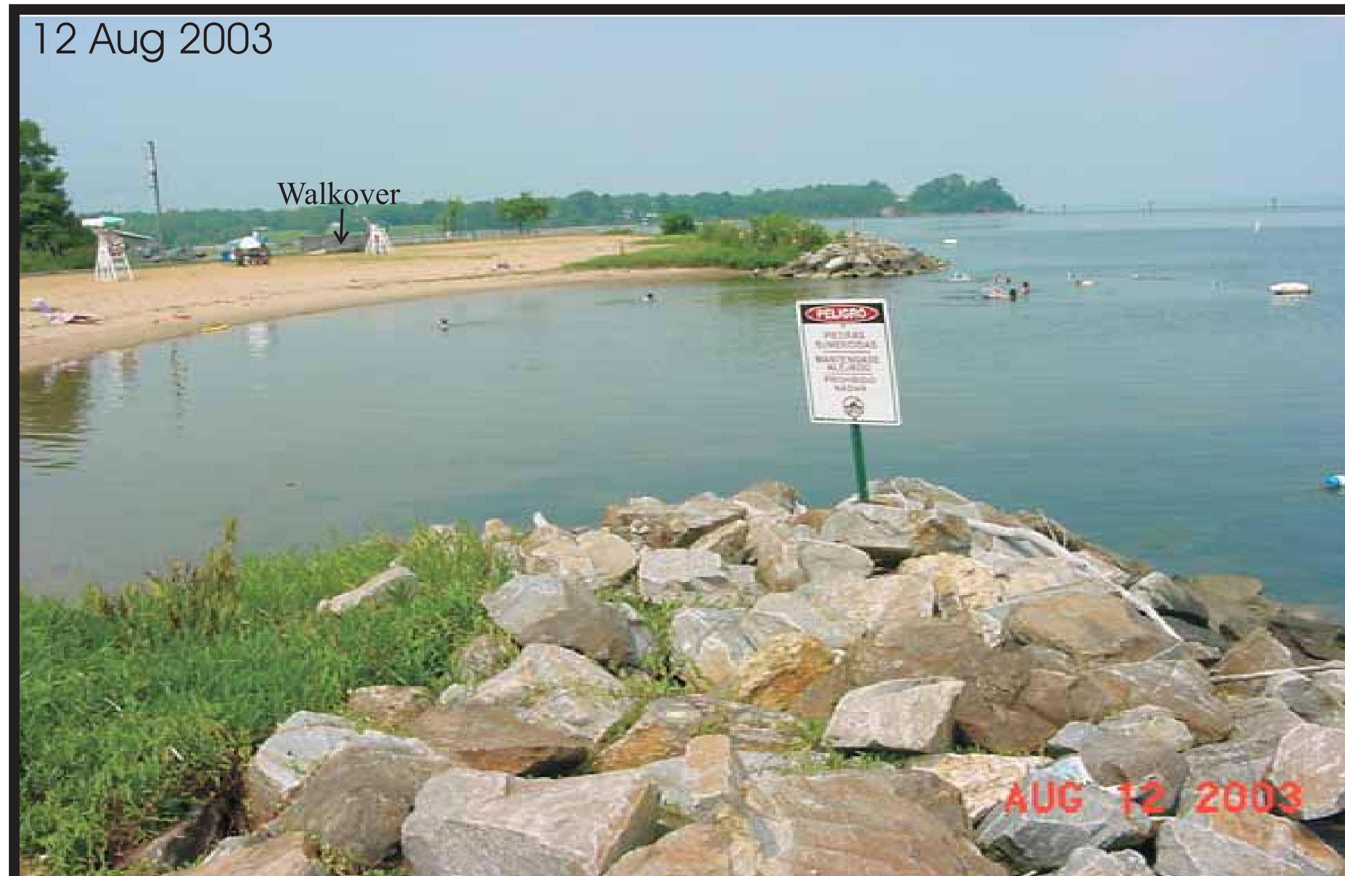


Figure 16. Aquia Landing baseline and selected pre and post storm cross-sections

Looking south along the Jersey wall and access road



Looking north from Bw 2

Figure 17. Aquia Landing ground photos before and after Hurricane Isabel.

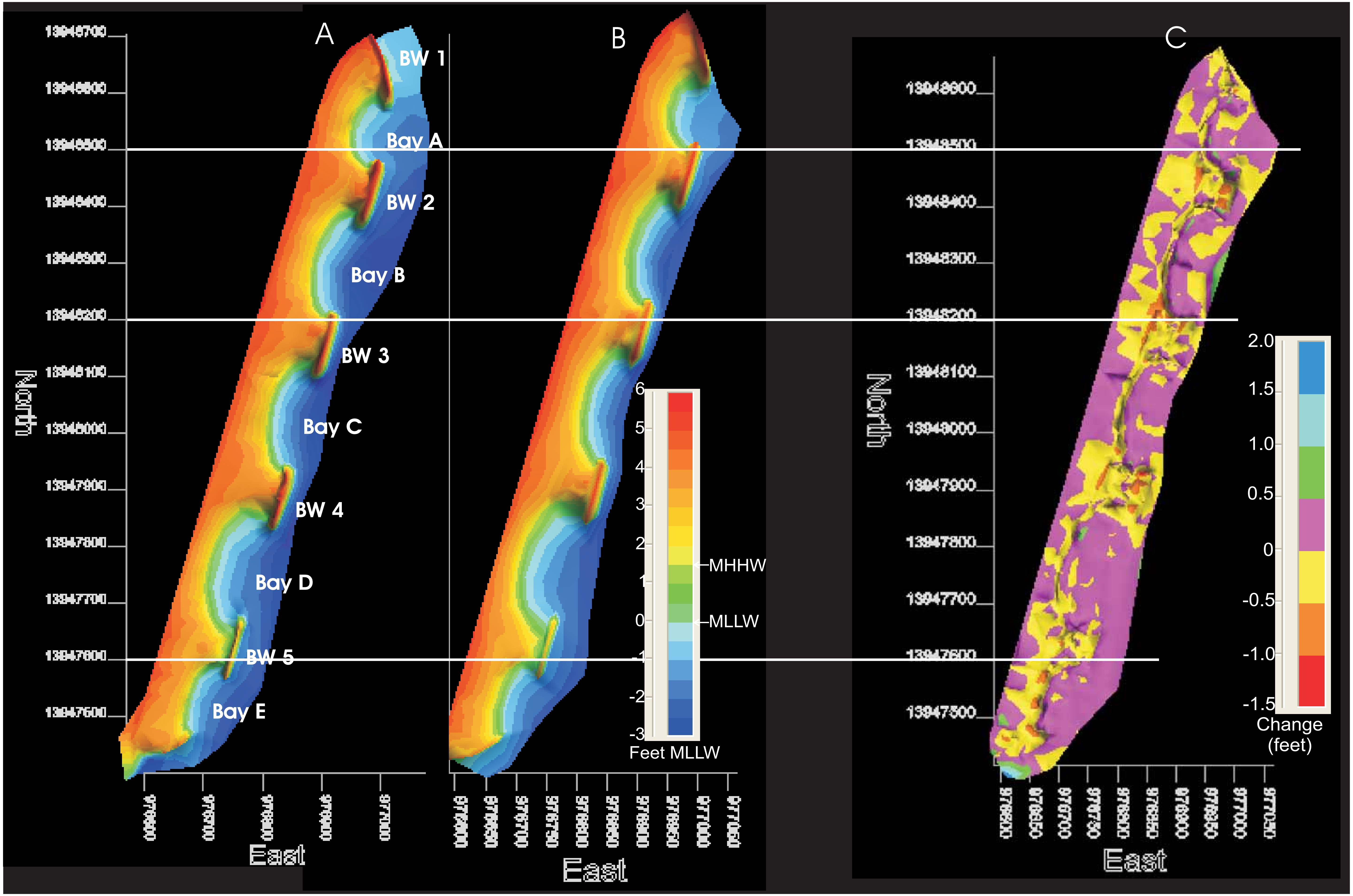


Figure 18. Aquia Landing color contour maps for the A) pre- and B) post-storm conditions, and C) isopach map showing elevation changes between surveys.

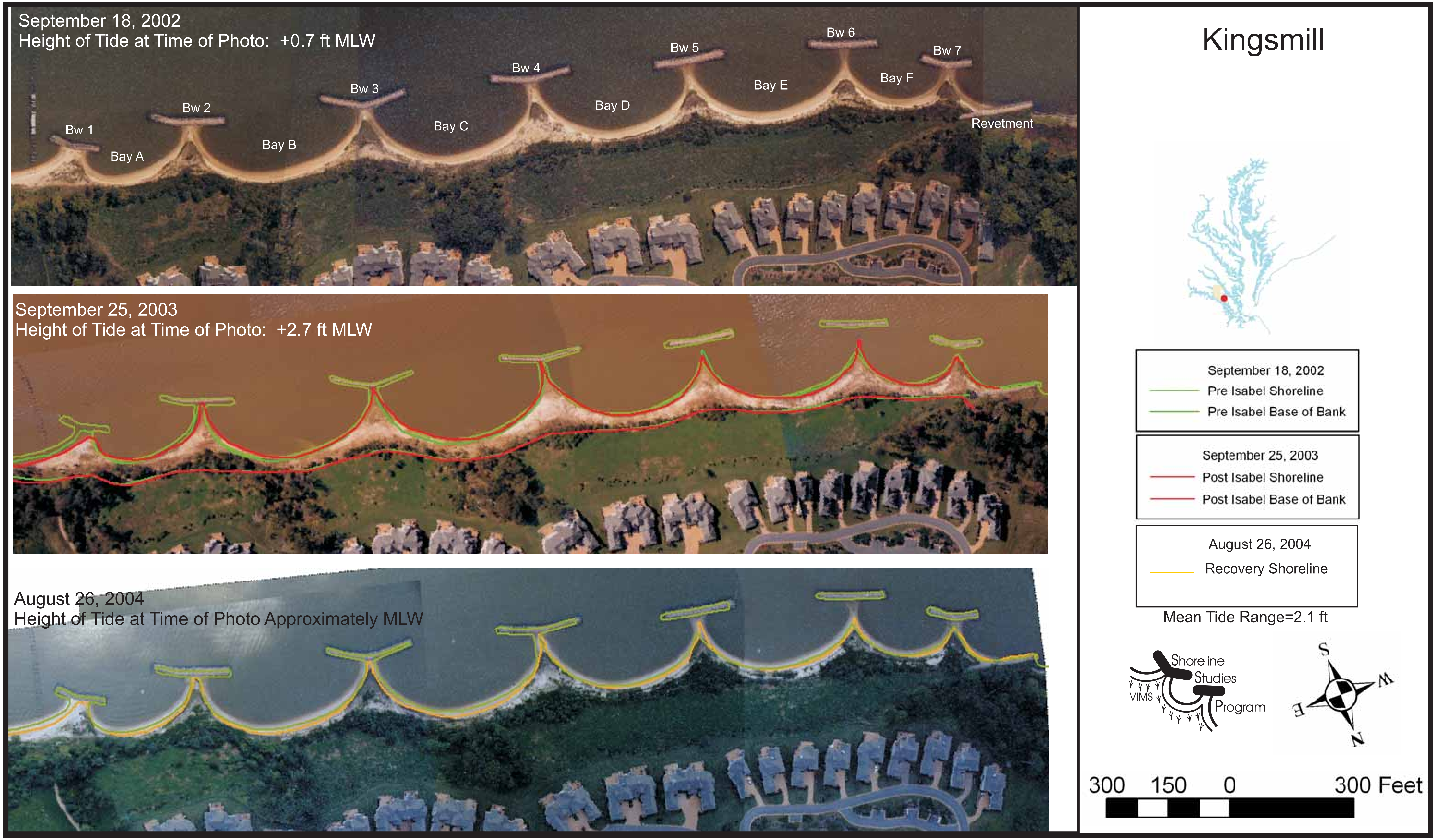


Figure 19. Kingsmill low-level pre- and post-Hurricane Isabel and recovery ortho-rectified aerial photos.

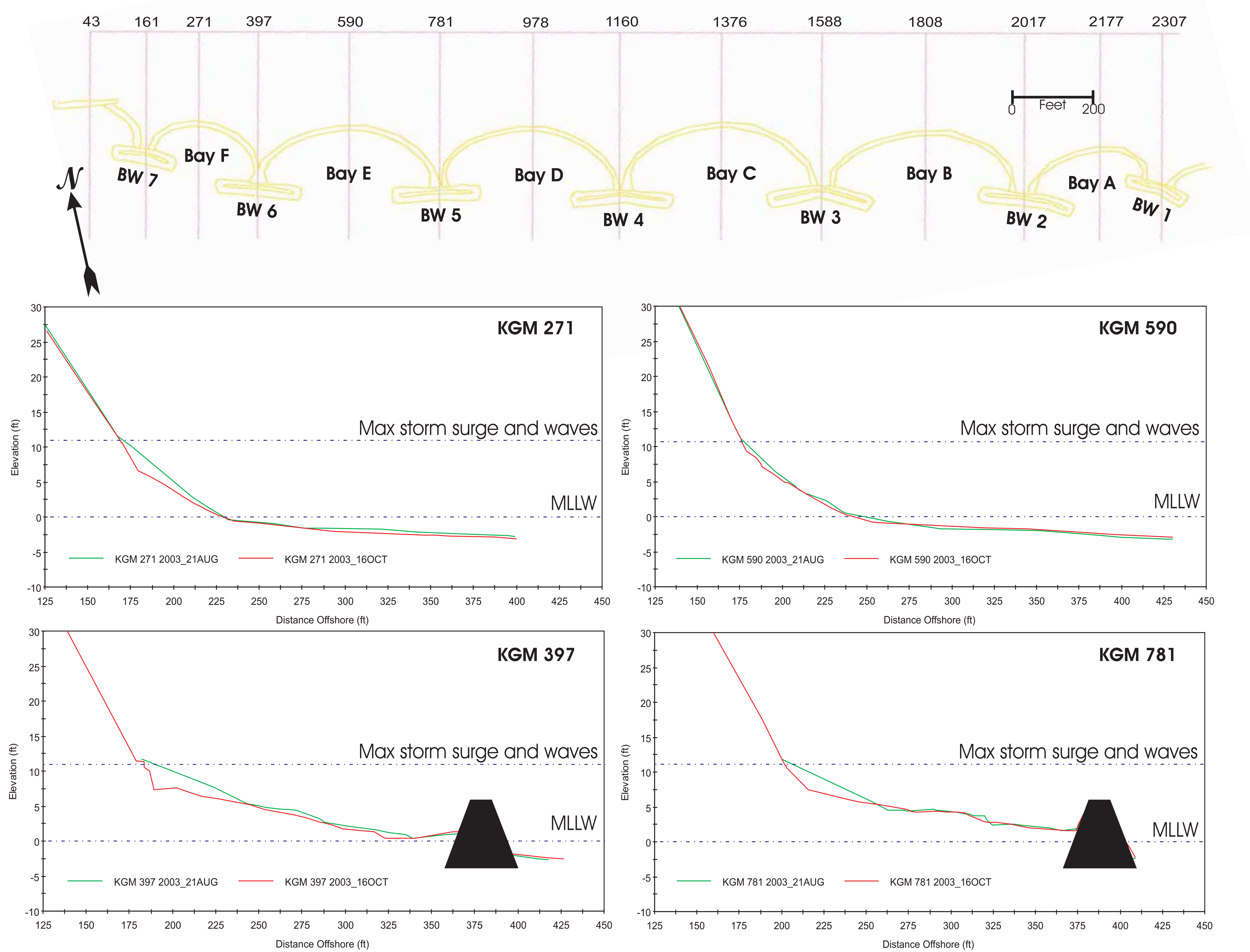


Figure 20. Kingsmill baseline and selected pre and post storm cross-sections.

Figure 21. Kingsmill ground photos before and after Hurricane Isabel.

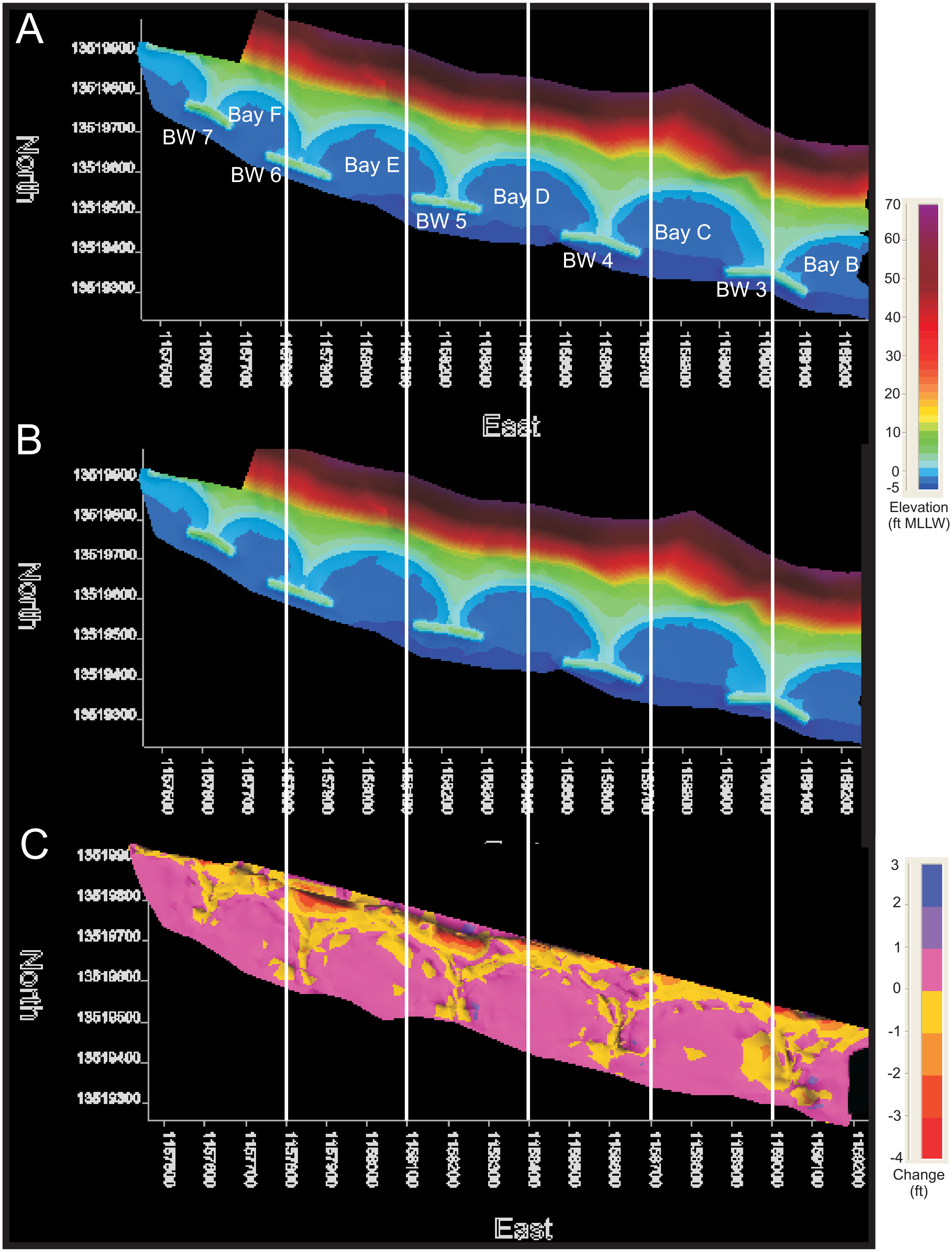


Figure 22. Kingsmill color contour maps for the A) pre- and B) post-storm conditions and C) isopach map showing elevation changes between surveys.

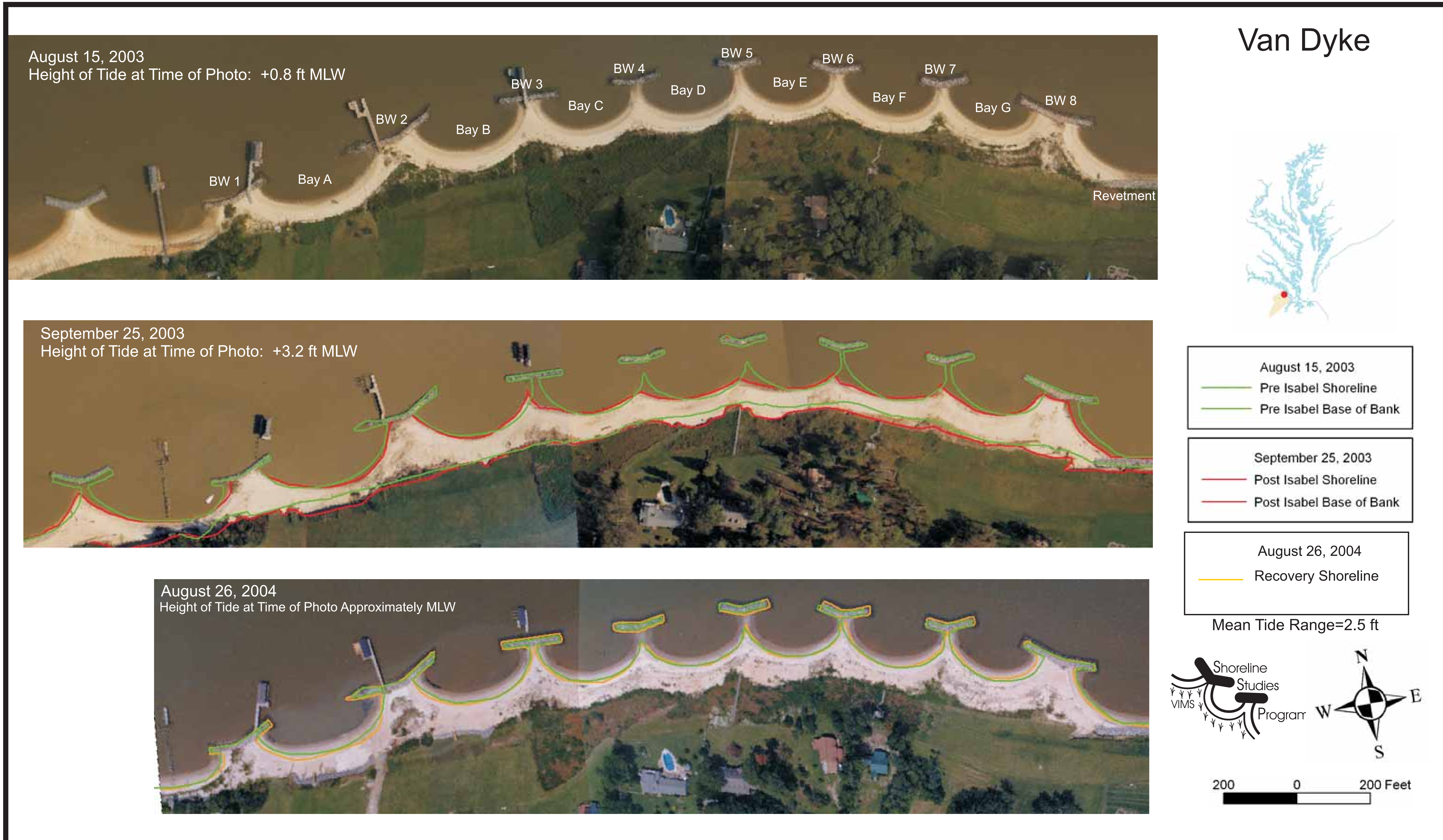


Figure 23. Van Dyke low-level pre- and post-Hurricane Isabel and recovery ortho-rectified aerial photos.

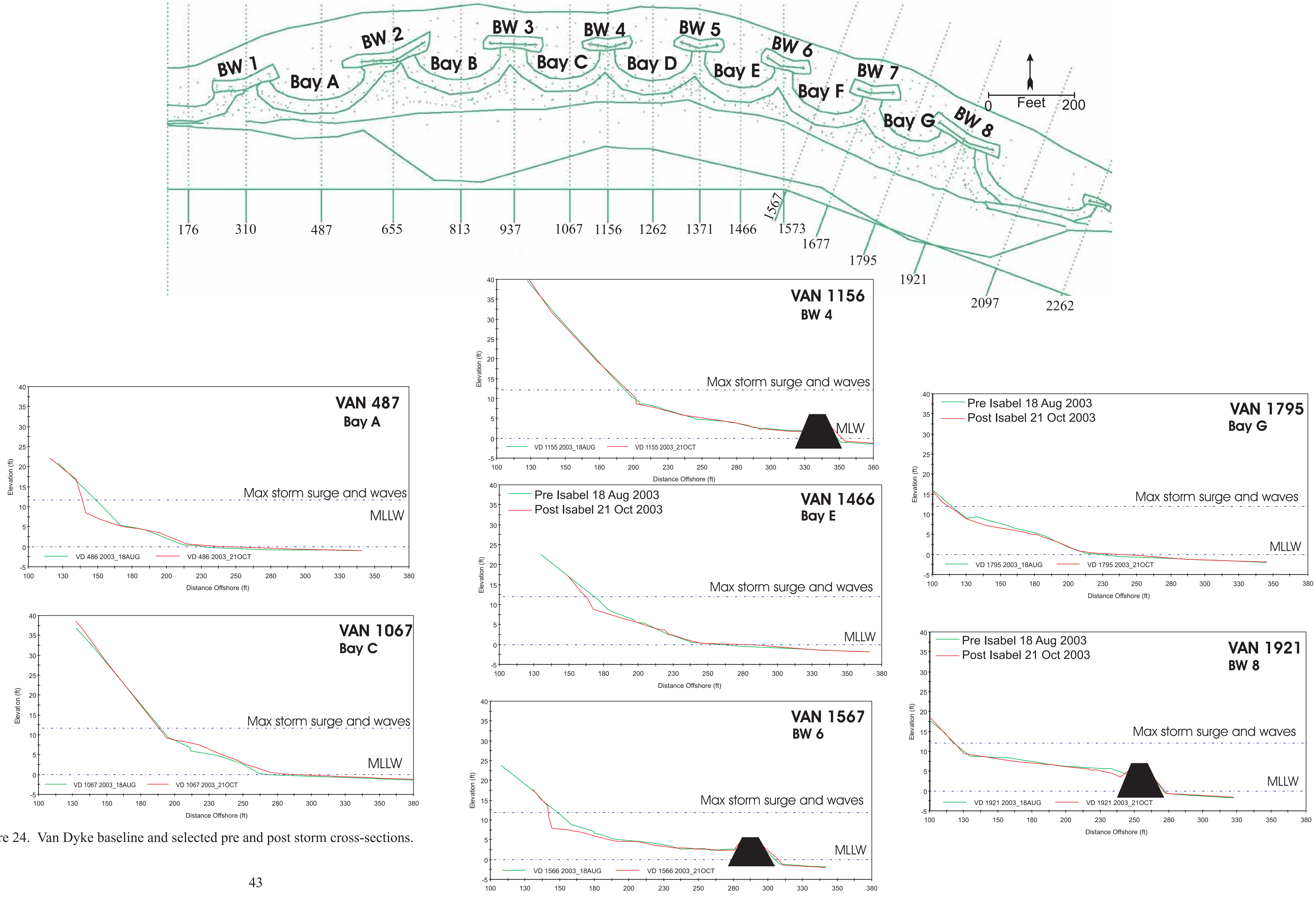


Figure 24. Van Dyke baseline and selected pre and post storm cross-sections.

Figure 25. Van Dyke ground photos before and after Hurricane Isabel.

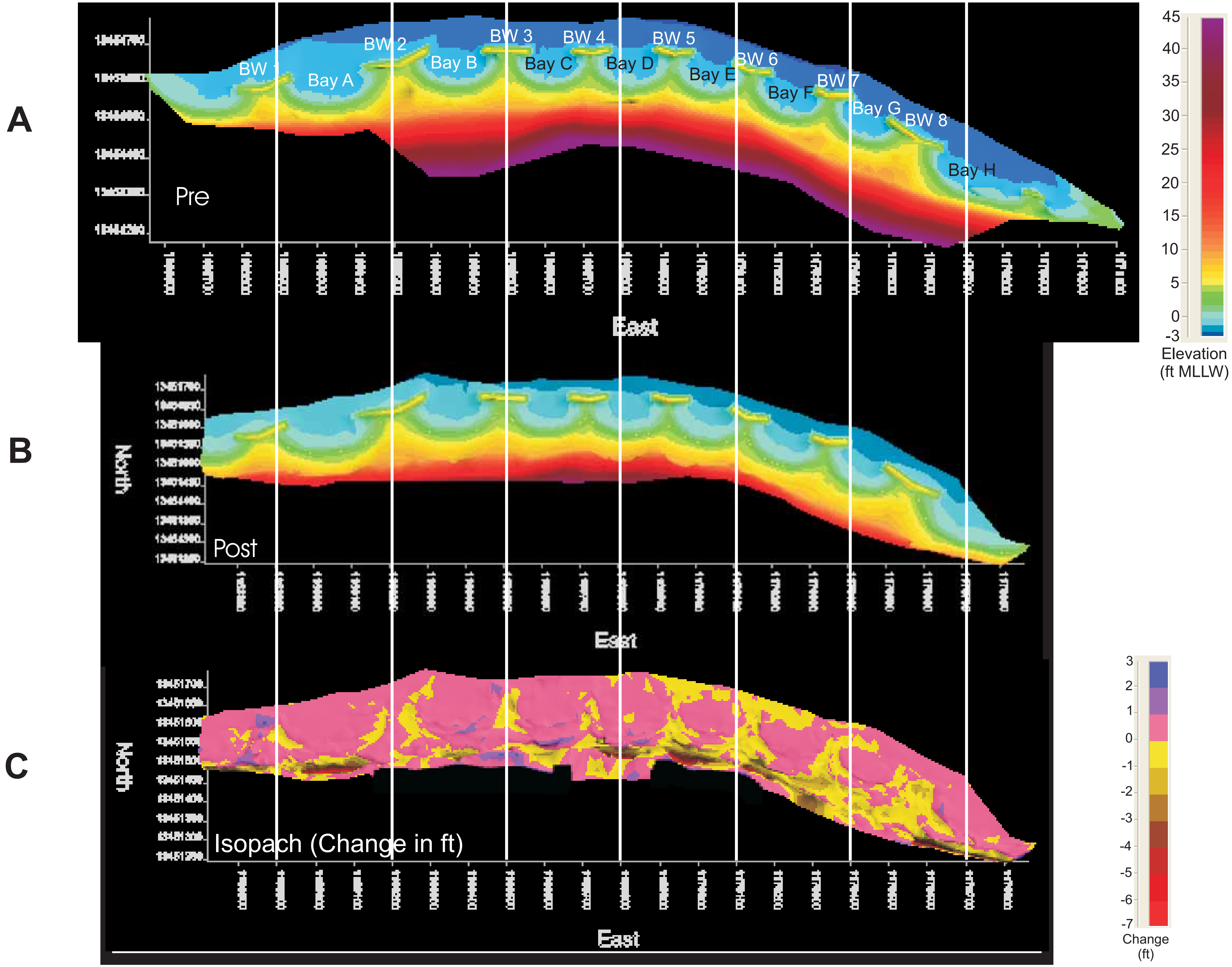


Figure 26. Van Dyke A) pre- and B) post-storm color contour maps, and C) isopach map showing elevation changes between surveys.

Figure 27. Yorktown low-level pre- and post-Hurricane Isabel and recovery ortho-rectified aerial photos.

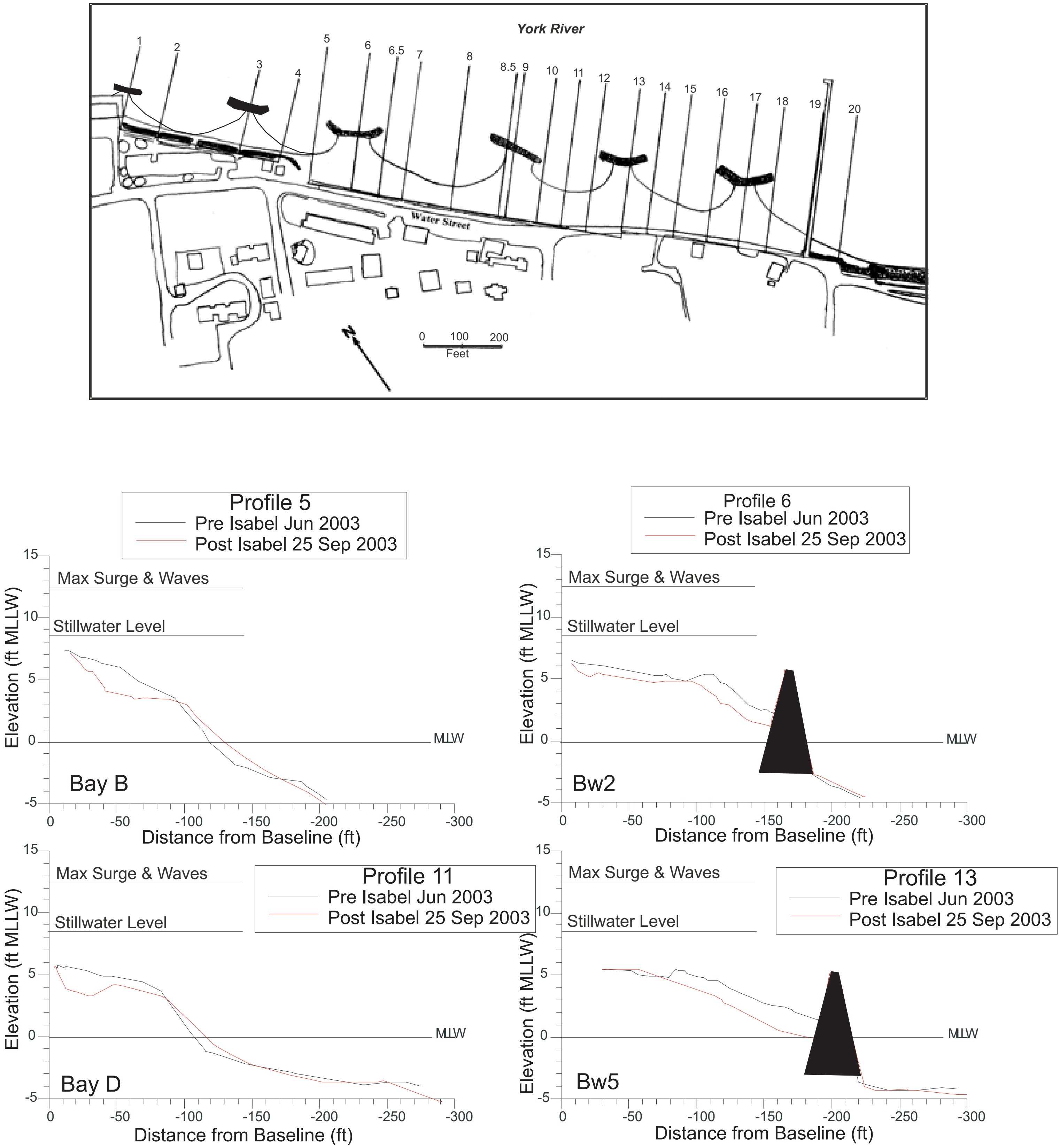


Figure 28. Yorktown baseline and selected pre and post storm cross-sections.

Figure 29. Yorktown ground photos before and after Hurricane Isabel.

Figure 30. Yorktown A) backshore and B) post storm wrack line and C) adjacent shore impacts.

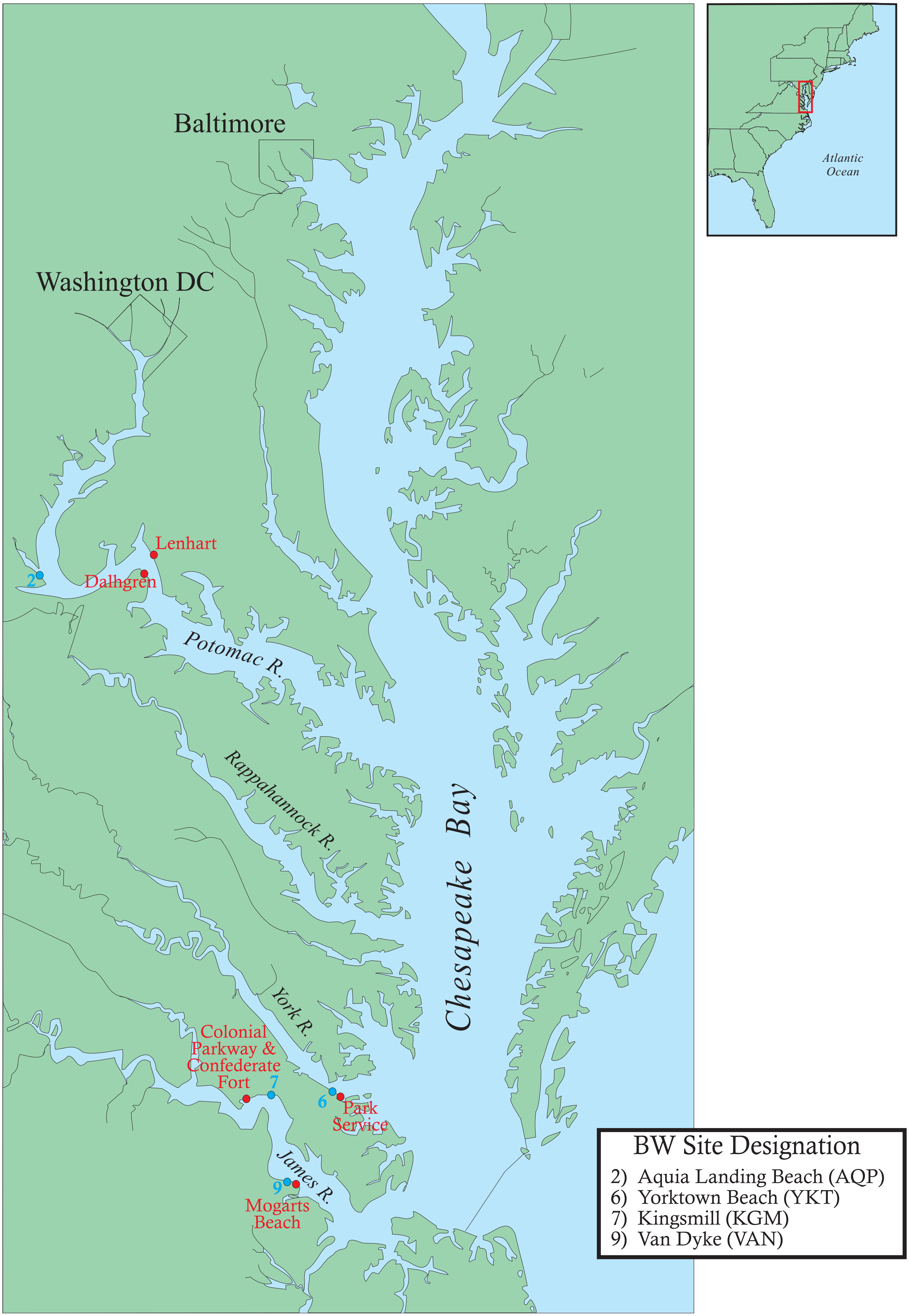


Figure 31. Location of breakwater sites used in this report (blue) and other impacted sites (red).

Figure 32. Impacts to the unprotected shore at Dahlgren due to Hurricane Isabel.

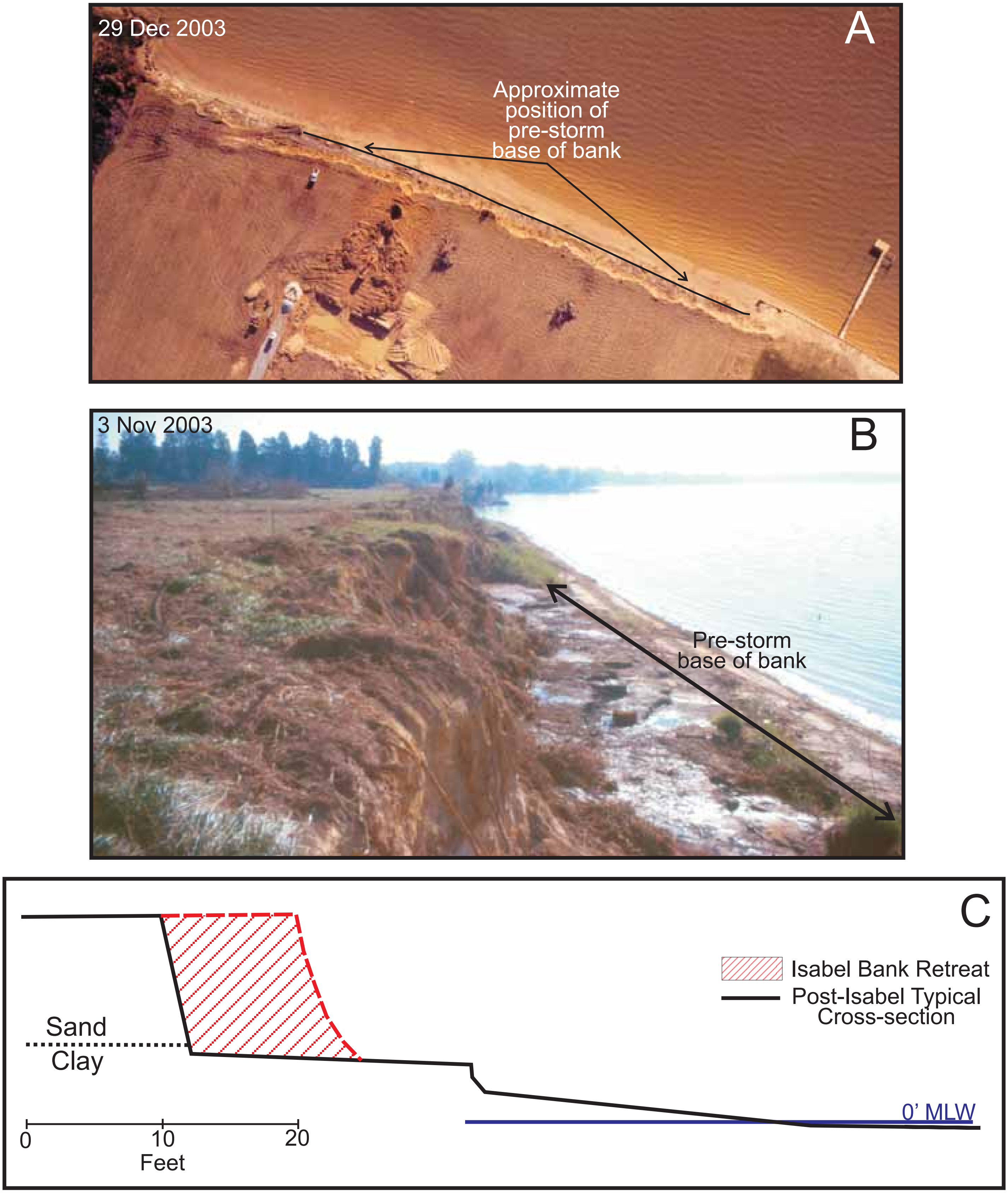


Figure 33. Impacts to the unprotected shore at Lenhart due to Hurricane Isabel shown A) on a non-rectified aerial photo, B) ground photo, and C) on a typical post-storm cross-section.

Figure 34. Impact to unprotected shores on the James River due to Hurricane Isabel A) at the Confederate Fort and B) along the Colonial Parkway.

Figure 35. Impacts at the downriver end of Van Dyke where the shore is protected by a revetment.

Figure 36. Impacts to the shore downriver from Van Dyke at Mogarts Beach.

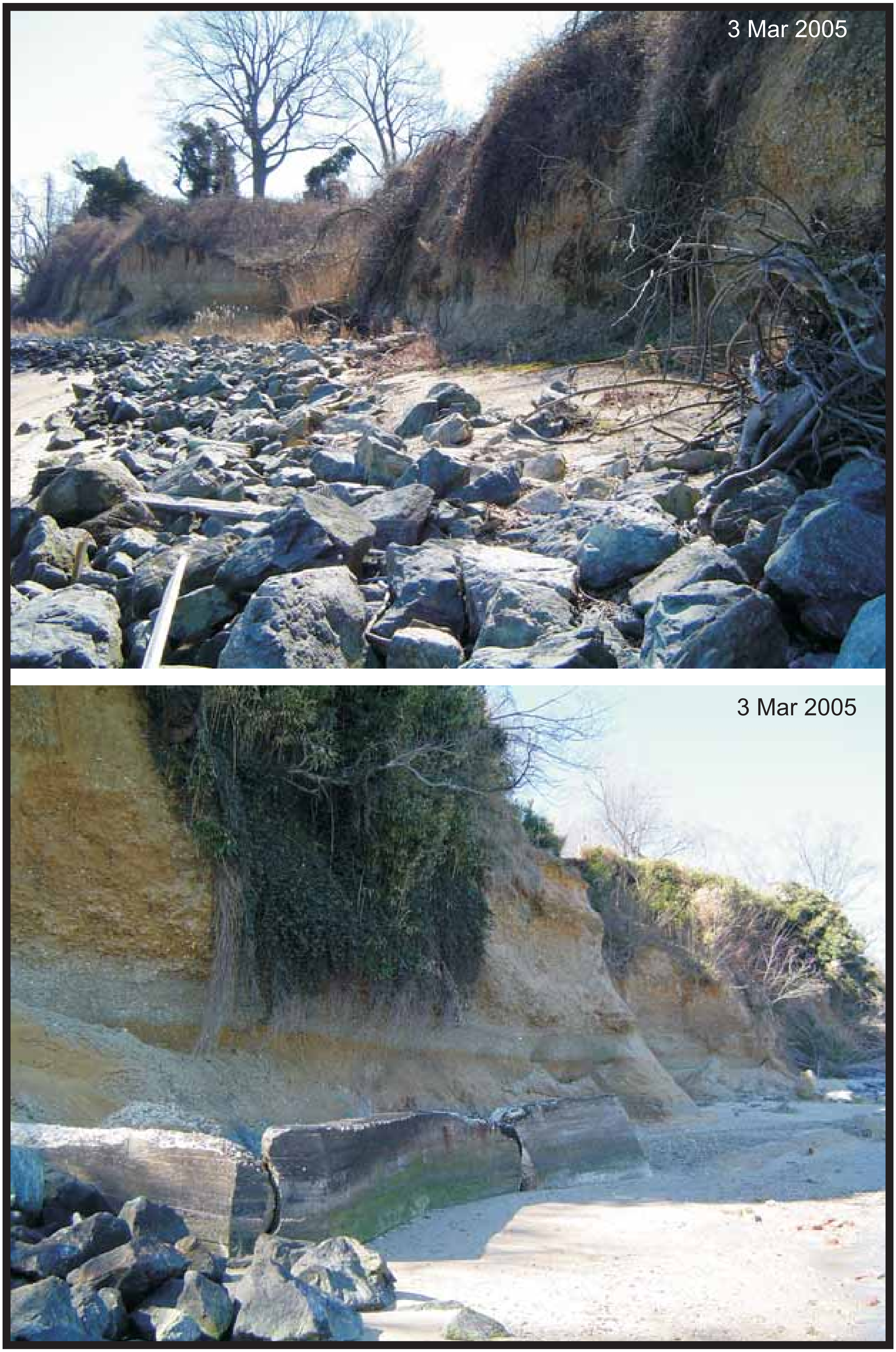


Figure 37. Impacts to the shoreline downriver from Yorktown Beach at the National Park Service's Moorehouse.